EECE 7296 - Major Project Written Report

Spin-Orbitronics: Spin-Orbit Torque Magnetoresistive Random Access Memory (SOT-MRAM)

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Abstract

Spin-Orbit Torque Magnetic Random-Access Memories (SOT-MRAMs) have emerged as promising candidates in the pursuit of energy-efficient and high-performance non-volatile memory technologies. This report delves into the background of SOT-MRAMs, emphasizing their significance in the context of energy consumption and technological importance. The discussion encompasses the working principles and underlying physics of SOT-MRAMs, paving the way for an exploration of materials crucial to their functionality. Our study elaborates thoroughly on the intricate physics underpinning the functionality of SOT-MRAMs, unraveling the mechanisms by which spin currents induce magnetic switching. An emphasis is placed on the dynamic interplay between spin and orbital angular momentum, elucidating how these torques manifest as writable and readable states in the memory cells. This discussion sets the stage for a nuanced exploration of the materials critical to the success of SOT-MRAMs. The conventional use of heavy metals in SOT-MRAMs is scrutinized, shedding light on the associated energy challenges and the need for alternative materials. Transitioning towards two-dimensional Transition Metal Dichalcogenides (2D TMDs) is proposed as a viable solution. The lattice symmetry and Spin-Orbit Coupling (SOC) efficiency of 2D TMDs are highlighted, showcasing their potential to revolutionize the landscape of SOT-MRAM materials. Our report concludes with a glimpse into the future of research in this domain, envisioning advancements that could propel SOT-MRAMs into mainstream memory technologies. This report provides a comprehensive overview of the evolution of SOT-MRAMs, accentuating the shift towards 2D TMDs as a transformative step. It captures the physics, materials, and challenges associated with this transition, setting the stage for future research endeavors in the quest for more efficient and sustainable non-volatile memory solutions.

1 Background

1.1 On the quest for a greener technology in information processing

The discovery of the transistor [1] and its integration into a single chip, forming an integrated circuit, marked a pivotal moment in human history. Since then, the focus has been on increasing the number of transistors on a chip through a scaling rule, exemplified by Moore's law [2], which doubles transistors per square inch, boosting computational power and shrinking device sizes.

These devices are now integral to our lives for computation, communication, and entertainment. However, the incessant demand for more computing power, combined with the rise in devices, poses a significant energy wastage challenge. This has led to a shift toward developing more energy-efficient devices.

For example, developed countries currently allocate about 5% of total electricity to information technology, and it is expected to increase in the following years. The power density of CPUs, like Pentium chips with over a billion transistors, approaches that of nuclear reactors, with current values of 100 W/cm^2 as seen in Fig. 1. Data centers, major energy consumers, follow their own energy-wasting trend in the "big data" era. Furthermore, the emergence of mobile devices (smartphones, tablets, watches, and glasses) surpassed desktop users in 2014, and their short battery life, stemming from power-hungry features, poses a critical challenge.

In conclusion, the urgent need for low-energy devices to align with the shift toward greener technology is evident. This project explores the ongoing research in the field of spin-orbitronics, in which various technologies are being investigated in the quest for energy-efficient computing devices.

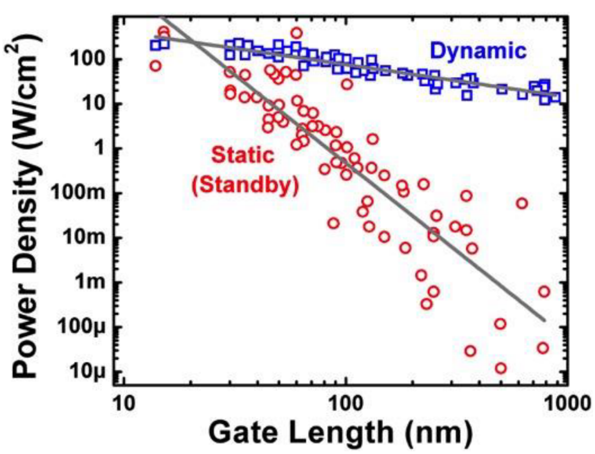

Figure 1. Power density of a CMOS transistor showing dynamic power and static power. As scales are reduced, the static power becomes more predominant, facing the same amounts of power for the smallest transistors [3].

1.2 Spintronics: Information coding via spin of the electron

The primary challenge with contemporary transistors lies in their efficiency during computation, utilizing approximately 1 femto-Joule (fJ) of energy per switch (referred to as dynamic power). However, a significant drawback is the comparable or even greater energy wastage when they are dormant (referred to as static power). This issue intensifies as transistors are scaled down to smaller dimensions (see Fig. 1). The underlying problem is that transistors, being charge-based devices, tend to leak in the dormant state. This leakage not only results in wasted energy but also compromises the stability of these devices, making them typically volatile when power is turned off.

Constructing devices using variables other than charges, which remain stable for extended periods, can entirely eliminate static power, leading to energy-efficient devices. Magnet-based memory, such as hard disks, utilizes the spin-state of electrons to store information (as opposed to charge) and has been employed for storing information over several years, making them natural candidates for this purpose.

Spintronics, a dynamic and expanding area of research, focuses on electrically controlling the spin degree of freedom to engineer devices for computation, sensing, and storage. In spintronics, information is encoded in the orientation of a collection of spins, with the spin configuration fixed at a local minimum of a designed energy landscape. The "leakage" of information occurs when the spin configuration changes to another local minimum due to thermal fluctuations-induced escape over a barrier. For magnets, it is relatively easy to design an energy barrier of approximately 40 k_BT [4], where k_B and T are the Boltzmann's constant and operating temperature, respectively. This corresponds to an escape rate of tens of years at room temperature, which is why information stored in magnets is considered "non-volatile."

While the standby power of spintronic devices being zero raises the question of why spintronic devices aren't more widespread, a major obstacle is the high dynamic power. In spintronic devices, unlike charge-based devices, the transmutation of electrical to magnetic energy must occur during the computation cycle to interface the magnets with electrical inputs and outputs. The dynamic power requirement for this electric control of magnets is a significant bottleneck in present-day spintronic devices and an area attracting intense research activity.

1.3 Mechanisms for electrical control of magnets

The essential characteristic for storing information in magnetic devices is the electron's spin. Spin is a quantum mechanical manifestation of angular momentum specific to electrons. Below a critical temperature called Curie temperature, when atoms come together to create a magnetic material, spin develops a net non-zero magnitude. In broad terms, two potential approaches have been investigated to manipulate information stored in spins: (a) altering the critical temperature and (b) exchanging angular momentum with the magnets, thereby applying torque to them.

Electric-field-controlled Curie temperature: Scientists wanted to find a way to control magnetism using electricity. They got inspiration from the success of changing the conductivity of semiconductors by adding certain substances (doping). This led to the discovery of dilute magnetic semiconductors (DMS). In DMS, magnetic properties are introduced into a non-magnetic semiconductor by adding a small amount of magnetic impurities. By doing this, they could combine the features of semiconductors with the properties of magnets. This combination allowed them to use established methods for controlling semiconductors using electricity.

Specifically, they found that by adjusting the number of electrically charged particles (carriers) in the semiconductor with an external electrical "gate", they could change the Curie temperature. The Curie temperature is the characteristic temperature at which a material loses its magnetic properties. So, by using the gate to control the number of carriers, they could, in turn, control the strength of the magnetic interaction between the added magnetic impurities. This interaction strength determines the Curie temperature.

The advantage of this method is that the use of electric fields for control of magnets allow for dynamic power comparable to CMOS transistors, however, the major challenge remaining for quite some time now has been to bring the operating temperature of DMS to the room temperature.

Spin transfer torque (STT): STT is a way of using electricity to make a magnet move. Imagine a sandwich made of layers as depicted in Fig. 2: a ferromagnet (PL), a non-ferromagnet in the middle, and another ferromagnet (FL). If the middle layer is a metal (or an insulator), it's called a spin-valve (or magnetic-tunnel junction). In this sandwich, one ferromagnet, PL, is set in a certain direction, and the other, FL, can move in any direction.

When you pass an electric current through this sandwich, the PL layer makes the current have more of one type of spin. This spin is then passed on to the FL layer, making it move in a specific direction. This allows us to control the magnet using electricity.

In simple terms, when the current goes through the magnet, only the parts of the current that match the magnet's direction get through. The rest is kind of absorbed by the magnet, making it move. This is the spin transfer torque. The amount of torque is related to how many electrons are in the current and how much spin they have.

This method is helpful because the electricity needed to make the magnet move depends on how much current is used, and it scales down with the size of the device. However, for very small samples, the energy required is still quite high. Recently, a new method called spin-orbitronics has been discovered to overcome these challenges, and we'll talk about that in the next section.

1.4 Scope of the report

In this project, the field of spin-orbitronics is explored which involves an examination of its fundamental concepts and operational mechanisms, highlighting recent discoveries made in the past few years. Spin-orbitronics is an extension of spintronics, with a specific focus on the spin-orbit coupling (SOC) of electrons within an atom. The investigation will particularly emphasize Spin-Orbit Torque (SOT) Magnetoresistive Random Access Memory (SOT-MRAM) technology. This technology leverages the principles of spin-

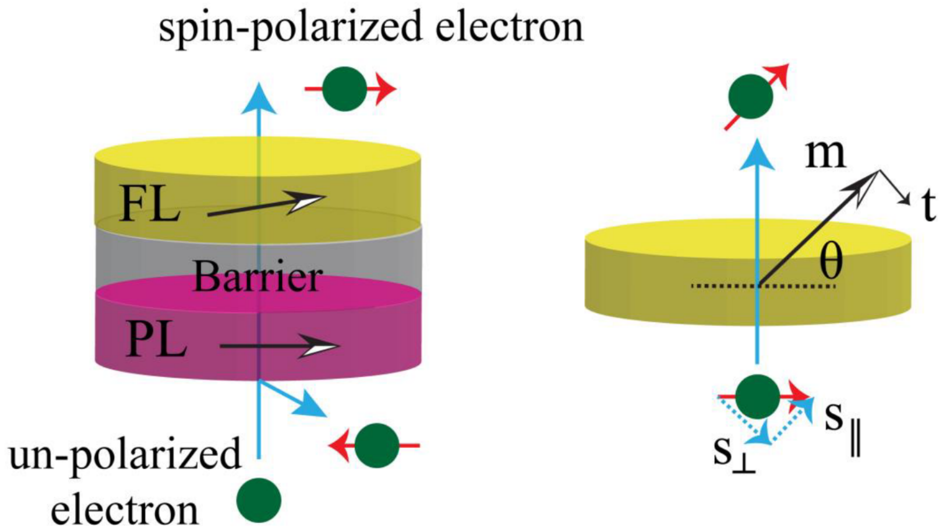

Figure 2. (Left) Angular momentum transfer from a pinned layer (PL) to a free layer (FL). These layers separated by a barrier forms the basic element of a magnetic tunnel junction (MTJ). Current passed through such a stack becomes spin polarized by PL which transfers angular momentum to FL. (Right) Illustration of spin-transfer-torque: Magnet filters spins transmitting only the parallel component to the magnetization (m) and absorbing the transverse component, and resulting in a torque [5].

orbitronics to capitalize on the non-volatility of magnetic elements for data storage. The project aims to provide insights into the advancements and applications within the realm of spin-orbitronics, shedding light on its potential in enhancing data storage technologies.

2 SOT-MRAM: Magnetization Switching by Spin-Orbit Torque

2.1 Spin-orbitronics, spin-orbit interaction as the coupling mechanism

In order to explain the physics behind the spin-orbit interaction, let us think of electrons as tiny dancers gracefully twirling around an atomic nucleus. Surprisingly, their dance has the power to influence magnets. If we can somehow connect their dance moves (which we can control with electricity) with the way they spin, it opens up a new way to make magnets move using a force called spin-orbit torques (SOT). This connection, often referred as the spin-orbit interaction (SOI), gives rise to two important effects in the world of spin-orbitronics: the Rashba effect and the Spin Hall effect. These effects can be understood as special dance moves electrons do around an atom.

Picture the microscopic world of electrons in materials like a dance floor where spins and motions create a unique performance. In this dance, two standout moves, the Rashba effect and the Spin Hall effect, become the stars.

The Rashba effect happens where materials with strong spin-orbit coupling meet structures without symmetry, like a dance floor with a special design. As electrons move in this space, an electric field adds a twist to their spins, creating a spiral pattern. Think of dancers syncing spins with the floor's unique design. This spin-momentum coupling, or the Rashba effect, is crucial in spintronics. Scientists use it to guide electron spins with electric fields.

Now, let's talk about the Spin Hall effect. In certain materials, when electrons move under an electric field, their spins line up perpendicular to their motion, forming a special pattern. Imagine dancers organizing themselves into groups based on spin as they move. This separation creates a pure spin current, a flow of electron spins without the usual charge movement.

In the big show of spintronics and spin-orbitronics, these effects act like exciting dance moves, guiding electron spins in patterns that could shape the future of electronic devices. They are a mix of style and function, letting scientists and engineers choreograph electron and magnet movements with super precision on the tiny dance floor of materials. Unlike the usual spin transfer torque method that uses a polarizing layer, using the dance moves of electrons for torques has its advantages. It is not limited by certain things, which means we might need less electricity, making the whole process more efficient.

Usually, this dance effect has a bigger impact on core electrons, those closer to the nucleus, which move faster and has stronger relativistic effect. Similarly, when dealing with heavier elements, there is a stronger connection between the spinning of electrons (spin-orbit coupling). This dance connection allows to control the way electrons move with electricity, affecting how magnets behave. So, it is like directing the movement of magnets using the dance of electrons powered by electricity.

The resistance of the MTJ is measured to determine the information stored in the read data of the SOT-MRAM. The sample with fixed magnetization is a comparable sample. As a sense current passes through the MTJ, the resulting voltage drop indicates a resistance condition. This readout method provides efficient and reliable data recovery.

2.2 Obtaining SOI with magnetic materials

Even though scientists have known about the influence of spin-orbit interaction on electrical transport for a while, the recent increased interest around spin-orbitronics comes from the ability to enhance this interaction in magnetic systems. Regular magnets, being lightweight, naturally have a weak intrinsic spin-orbit coupling. However, as we discussed earlier, a strong spin-orbit interaction needs the presence of heavy elements.

So, there are two ways to make magnets connect with spin-orbit interaction. On the one hand, magnetic thin films can be interfaced with heavy-metal systems, like Platinum, Tantalum, Tungsten, and Bismuth-doped Copper. On the other hand, magnetic properties can be introduced to materials that already have high intrinsic spin-orbit coupling '[6]. For example, use Cr-doped Bismuth selenide compounds or Manganese-doped Gallium Arsenide.

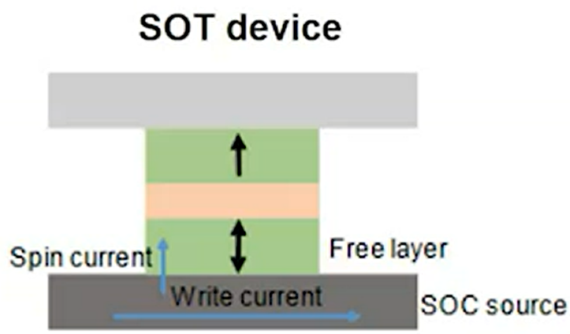

Figure 3. Typical structure of a SOT-MRAM [7].

2.3 Structure and working of SOT-MRAM

The basic structure of SOT-MRAM is similar to that of conventional MRAM but with a unique mechanism for manipulating the magnetic state of the memory cell. Like other types of MRAM (see Fig. 3), SOT-MRAM includes MTJs. It turns out that these layers consist of fixed layers and free layers. A heavy metal layer is added near the free layer of the MTJ. Common heavy metals include tantalum (Ta), tungsten (W), or platinum (Pt). These heavy metals are critical for generating SOT. The heavy metal surface facilitates SOC, which is the interaction between the spin of an electron and its orbital motion [7]. This interaction generates a SOT that can be used to change the magnetic state of the free layer. The interface between the heavy metal layer and the free layer is designed to maximize the SOT generation.

In the implementation of the SOT-MRAM, a SOT is applied to change the magnetic state of the free layer in the MTJ. That includes the following steps: when an electric field is applied to a heavy metal, the SOC effect induces a torque in the magnetic moment of the free layer. This torque changes the magnetization of the free layer, allowing data to be written to the memory cell. The resistance of the MTJ is measured during the reading task. The ratio of the magnetic moments of the reference and free layers determines the resistance. The readout function is based on the Tunnel Magnetoresistance (TMR) effect similar to other MRAM technologies. The performance of the SOT is affected by the choice of heavy metal, the interface between heavy metal and the free layer.

SOT-MRAM is a sophisticated technology that exploits the TMR effect for data writing, storage, and reading. This new approach to memory design holds the promise that it will improve non-volatile memory design in various applications. The TMR effect, a fundamental principle in MRAM technology, plays an important role in SOT and MRAM applications. The MTJ is central to this memory system.

2.4 Magnetic tunnel Junction

The MTJ is an essential building base of spin-based cutting-edge virtual gadgets. The running of an MTJ includes the manipulation of the spin in one among its layers, and the spin distinction among the two

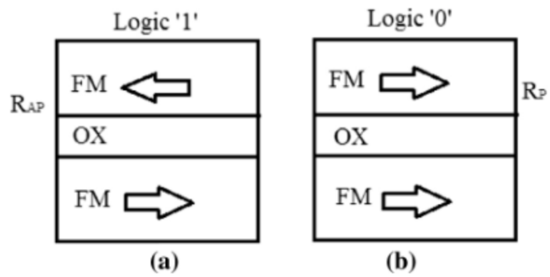

Figure 4. Schematic of the MTJ nano-pillars. Here, the below layer is fixed while the top layer is free. An oxide layer of thickness nm is sandwiched between FM layers [8].

layers may be used to store either logic 1 or logic 0 (see fig 4). MTJ includes 3 layers: a fixed magnetic layer, an insulating tunnel barrier, and a free magnetic Layer. The basic shape of an MTJ incorporates two ferromagnetic layers separated by thin insulating barrier [8]. The ferromagnetic layers function the electrodes, at the same time as the insulating layer acts as the barrier for electron tunneling. The magnetic orientations of the two ferromagnetic layers can be manipulated to create different states.

The important precept behind an MTJ's operation is spin-structured delivery. Electrons have a property known as spin, which can be either up or down. The MTJ exploits the spin-structured properties of electrons for data storage. When the magnetic moments of the two ferromagnetic layers are aligned parallel (parallel configuration), the tunneling possibility of electrons is higher. Conversely, when the magnetic moments are antiparallel (antiparallel configuration), the tunneling chance is decreased. The distinction in tunneling probability between the parallel and antiparallel configurations is known as TMR. TMR is an essential factor for the functionality of the MTJ. An external magnetic subject orients the magnetic moments of the loose layer. The route of the free layer's magnetic moment determines the spin-dependent current characteristics. A small voltage is implemented across the MTJ, and the ensuing tunneling resistance is measured. The resistance of the MTJ adjustments relies on the magnetic moments' relative alignment. During a write operation, a larger outside magnetic field orients the magnetic moments, efficaciously flipping the course of the free layer's magnetic moment. Binary data (0s and 1s) are saved primarily based on the resistance state of the MTJ. If the magnetic moments are parallel, it represent one binary state, and if they're antiparallel, it represent the alternative state.

MTJs keep their resistance state even if power is off, making them suitable for non-risky memory packages. Reading and writing operations in MTJs are enormously rapid compared to different non-volatile memory technologies. MTJs can endure an excessive range of write cycles without massive degradation, contributing to their sturdiness. MTJs perform with especially low power consumption, especially at some stage in read operations. MTJs are a fundamental element in MRAM, a form of non-risky memory that mixes the velocity of static RAM with the non-volatility of flash memory. MTJs are used in numerous magnetic sensor applications, along with magnetic area sensors for compasses and different digital gadgets. MTJs also are

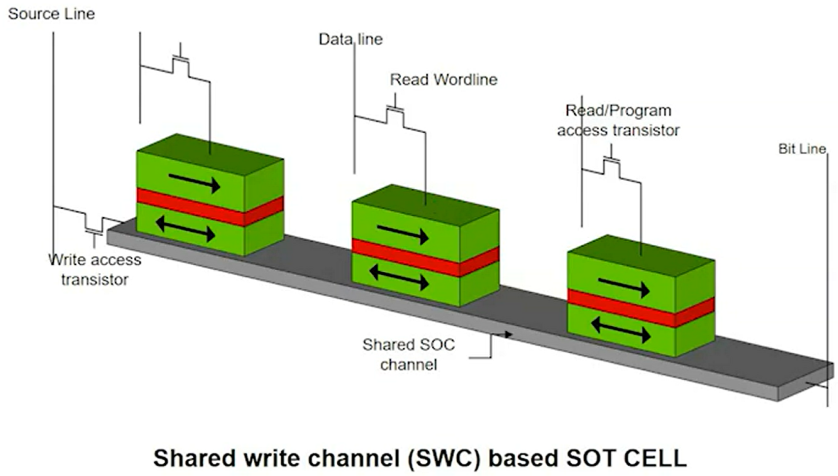

Figure 5. Shared-write-channel (SWC) based SOT memory design. Multiple bits sharing a common SOC source with a write-access transistor at the end of the channel. SOC channel underneath individual bits should be dynamically programmable to toggle the SOT polarity in order for the SWC memory architecture to work [7].

hired in some advanced tough disk force technology for reading and writing records [9].

2.5 Writing, Storing, and Reading in SOT-MRAM

SOT-MRAM has two different lines for read and write purposes (see Fig. 5). When it comes to writing data in SOT-MRAM, the TMR effect is exploited by applying a SOT. Using an electrode to manipulate the magnetic orientation of the free layer in the MTJ allows data to be efficiently written to the memory cell. This process not only enables writing speed but also contributes to the overall energy efficiency of SOT-MRAM. The information stored in SOT-MRAM is obtained by using the TMR effect to represent two states. The resistance state of the MTJ determines whether the memory cell stores a logical 0 or 1. Parallel alignment of magnetizations results in a low resistance state (LRS), while odd parallel alignment results in a high resistance state (HRS). The resistance of the MTJ is measured to determine the information stored in the read data of the SOT-MRAM [7]. The sample with fixed magnetization is a comparable sample. As a sense current passes through the MTJ, the resulting voltage drop indicates a resistance condition (see Fig. 6). This readout method provides efficient and reliable data recovery.

2.6 Unique characteristics of SOT-MRAM

The integration of the TMR effect in SOT-MRAM offers several advantages. The small size of the MRAM cells, as well as the scalability of the TMR effect, contribute to robust data storage. The indestructibility of the memory ensures that information remains available during power cycles, making it suitable for a wide range of applications [10].

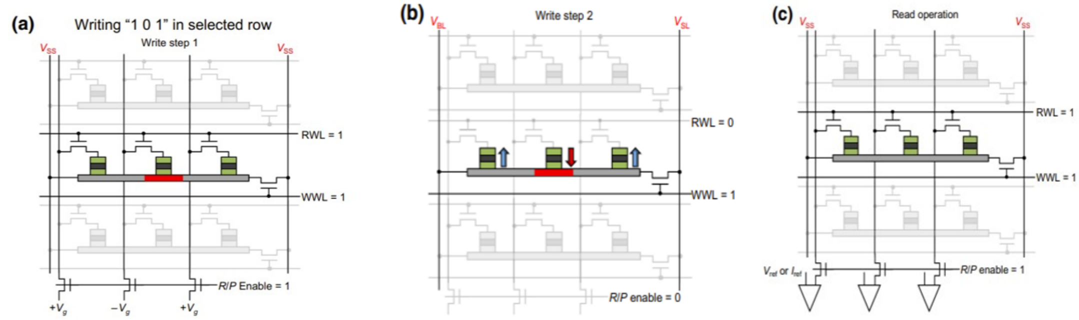

Figure 6. (a) First step during the write operation, which involves programming different bits of the selected row with varying SOT polarity. In the illustration, the middle bit is programmed with $-V_g$ SOT, while the other 2 bits are programmed with $+V_g$ SOT. (b) The second step of the write operation, passing a unidirectional current through the selected row to write the desired information. In the given example, the middle bit is switched to the down state, while the bits on either side are switched up. (c) Reading operation for the SWC memory. V_{SS} represents ground nodes [9].

SOT-MRAM, with its foundation in the TMR effect, represents a major advance in-memory technology. His work spans a variety of industries, including consumer electronics, automotive systems, and emerging technologies such as neuromorphic computing. As ongoing research and development in this area continues, the collaboration between TMR and SOT-MRAM has the potential to reshape the landscape of non-volatile memory systems, delivering faster, more responsive solutions reliable and energy-efficient for the digital age.

Compared to other MRAM technologies, it requires lower write rates, resulting in reduced power consumption and operating temperature. High-speed performance, comparable to STT-MRAM, makes SOT-MRAM suitable for applications that require fast data acquisition (see Fig. 7). Furthermore, its scalability ensures compatibility with advanced semiconductor manufacturing processes, enabling the development of high-capacity memory solutions. The low write density in SOT-MRAM increases the durability of the memory cells, making them ideally suited for applications involving multiple write cycles. This characteristic combined with non-volatile memory characteristics makes SOT-MRAM a promising candidate for applications, including embedded systems, mobile devices, cache memory, and data centers [11].

3 2D materials for efficient spin orbit interaction

3.1 Devices based on spin polarized current

Devices functioning based on spin torque often rely on two major mechanisms to produce the spin polarized current (a current which is not spin neutral) necessary for generating the required spin torque. A group of devices resort to STT mechanism, while the others depend on SOC to provide the essential spin torque. In

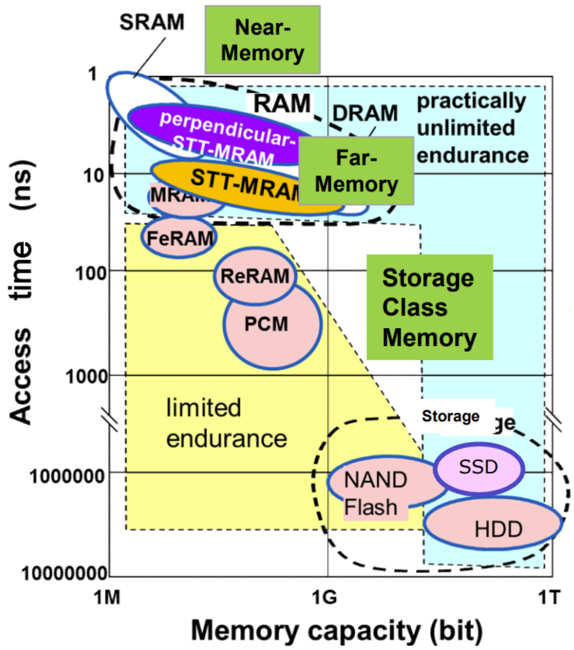

Figure 7. Memory capacity vs access time [11].

the former, spin polarized current is injected vertically through the device to supply it with the required spin torque. On the other hand, the latter procedure takes advantage of a charge current to produce the vital spin polarized current exploiting SOC mechanism. In both the aforementioned platforms, generation and presence of an spin polarized current is crucial, thereby it is essential to come up with an efficient procedure to produce it. In this report, the attention is mostly given to the generation of spin torque through SOC, therefore the emergence of 2D materials in spin-orbitronics is elaborated in the following.

3.2 Applications and limitations of 3D heavy metals

Conventional 3D heavy metals, such as Pt, Ta, and W are primarily used in the devices based on SOC due to their high atomic mass. In fact, SOC is relativistic phenomenon as it depends on the mass and speed of the electrons. Therefore, molecules with higher atomic mass are suitable candidates for devices functioning based on SOC. Even though 3D heavy metals can be used to offer SOC, they suffer from to major drawbacks. First, they provide a poor spin orbit coupling efficiency due to their simple crystal structure. Besides, as the lattice structure is mostly face centered cubic (FCC) for 3D heavy metals as shown in Fig. 8, they own unwanted crystal symmetry groups such as two-fold rotational symmetry which prevents from generating out-of-plane spin torque crucial for various applications.

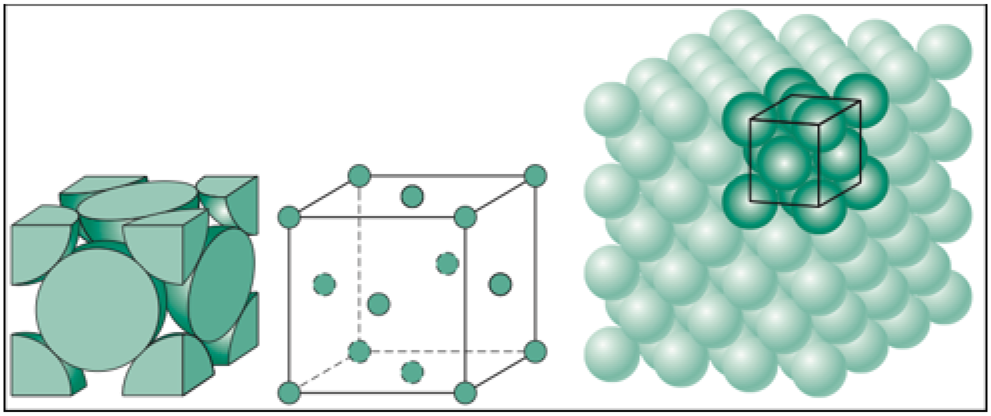

Figure 8. Schematic depiction of a FCC unit cell. [12].

3.3 3D magnetoelectric pseudo tensor and symmetry groups in lattice structures.

In devices based on SOC, a charged current with density of $\boldsymbol{j}$ is injected through the device resulting in a spin polarized current with density of $\boldsymbol{\sigma}$ which is connected to the charge current density as described below:

$$\boldsymbol{\sigma} = \boldsymbol{\chi}\boldsymbol{j}, \tag{1}$$

in which $\boldsymbol{\chi}$ is 3D magneto electric pseudo tensor defined in the following:

$$\boldsymbol{\chi} = \begin{bmatrix} \chi_{xx} & \chi_{xy} & \chi_{xz} \\ \chi_{yx} & \chi_{yy} & \chi_{yz} \\ \chi_{zx} & \chi_{zy} & \chi_{zz} \end{bmatrix}. \tag{2}$$

If the lattice holds a symmetry group $\mathbf{R}_s$, its magnetoelectric pseudo tensor remains unchanged under transformation through R_s as follows:

$$\boldsymbol{\chi} = \det(\mathbf{R}_s)\mathbf{R}_s\boldsymbol{\chi}\mathbf{R}_s^{-1}. \tag{3}$$

Therefore, the symmetry groups in the lattice can determine whether there exist a non-zero $\boldsymbol{\chi}$ and what its non-zero entries are. For instance, the symmetry group for a lattice containing inversion symmetry can be defined using the inversion operation given below:

$$\mathbf{R}_i = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \tag{4}$$

which can be applied to the magneto electric pseudo tensor to define its behavior:

$$
\begin{bmatrix} \chi_{xx} & \chi_{xy} & \chi_{xz} \\ \chi_{yx} & \chi_{yy} & \chi_{yz} \\ \chi_{zx} & \chi_{zy} & \chi_{zz} \end{bmatrix} = \det(\mathbf{R}_s)\mathbf{R}_s\boldsymbol{\chi}\mathbf{R}_s^{-1} = - \begin{bmatrix} \chi_{xx} & \chi_{xy} & \chi_{xz} \\ \chi_{yx} & \chi_{yy} & \chi_{yz} \\ \chi_{zx} & \chi_{zy} & \chi_{zz} \end{bmatrix}. \quad (5)
$$

Solving Eq. 5 will result in $\boldsymbol{\chi} = 0$, stating that a system with inversion symmetry group does not support SOC. Among all the symmetry groups available, there are only 18 groups that lead to a non-zero magnetoelectric tensor [13]. A SOC layer interfaced with a ferromagnetic material can provide a non-zero spin polarized current, however the undesired symmetry groups prevent from an out-of-plane torque to emerge.

3.4 Transition metal dichalcogenides and broken n-fold symmetry

As shown in Fig. 9, the combination of a SOC layer and a ferromagnetic material shape the lattice in a device functioning based on SOC. Conventional devices take advantage of heavy metals as their SOC layer, which can provide an acceptable SOC efficiency. However, the lattice made of the combination of a heavy metal interfaced with a ferromagnetic layer holds two-fold rotational symmetry which does not allow for a non-zero out-of-plane torque. An out-of-plane torque is essential for various purposes, including efficient switching, reduced power consumption, device scalability, and improved endurance and reliability.

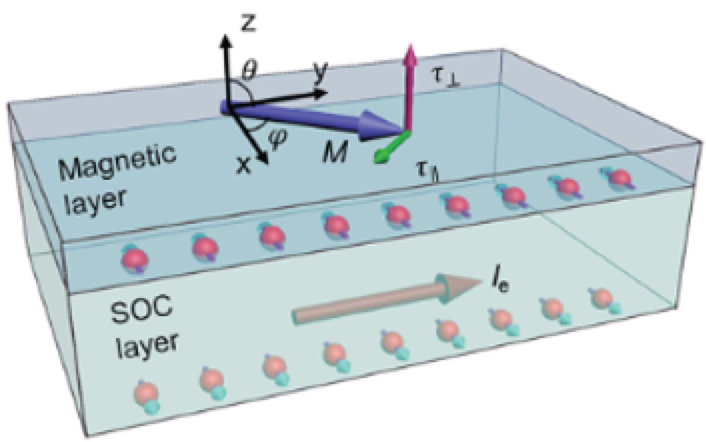

Figure 9. Schematic of a SOC layer interfaced with a ferromagnetic material in a SOC-based device [13].

In fact, the out-of-plane torque helps in efficiently switching the magnetization direction of the storage layer in the MTJ. This is crucial for fast and reliable write operations in the memory device. By applying an electric current perpendicular to the plane of the MTJ, the out-of-plane torque can facilitate the efficient manipulation of the magnetic state. Besides, SOT-MRAM is known for its potential in reducing power consumption compared to other MRAM technologies. The non-zero out-of-plane torque contributes to this advantage by allowing for lower current densities to achieve the required torque for switching. Lower current densities lead to reduced energy consumption, making SOT-MRAM a more energy-efficient option. SOT-

Figure 10. Configuration of SOC devices based on parallel and perpendicular magnets.

MRAM has shown promise for scalability to smaller device sizes. The out-of-plane torque plays a role in enabling the stability and reliability of magnetization switching at smaller scales. This is essential for the continued advancement of memory technologies as demands for higher storage density and smaller form factors increase. The non-zero out-of-plane torque can contribute to the endurance and reliability of SOT-MRAM devices. Efficient switching and reduced power consumption help in minimizing wear and tear on the materials, leading to a longer lifespan and improved reliability of the memory cells.

Transition Metal Dichalcogenides (TMDs) are a class of 2D materials with great SOC efficiency and appropriate symmetry groups for controlling both in-plane and out-of-plane magnets. To be more specific, some crystals structures in this class of 2D materials break the n-fold rotational symmetry and provide the possibility for generation of non-zero out-of-plane spin torque, which is essential for controlling perpendicular magnets as shown in Fig. 10. The unique crystal structure combined with the presence of relatively heavy transition metals can lead to a good SOC efficiency which alongside the desired symmetries in their structures, make them suitable candidates to replace heavy metals in the devices functioning based on SOC.

3.5 Molybdenum disulfide and its different phases

In this subsection, molybdenum disulfide (MoS_2) in different phases is investigated as a 2D TMD materials in terms of its lattice structure and tuanibility. Although it has been mentioned in this report that 2D TMDs can be exploited to break the unwated symmetry groups, not all of them open up this avenue. As an illustration, the lattice structures are given in Fig. 11 for different phases of MoS_2. As can be observed, the lattice preserves its n-fold rotational symmetry in $3R$, $2H$, and $1T$ phases, therefore they cannot provide the possibility for the generation of out-of-plane torque. On the other hand, as shown in Fig. 11(b), the $1T' - MoS_2$ can introduce a crystal with the desired broken symmetries for the generation of the favorable out-of-plane torque.

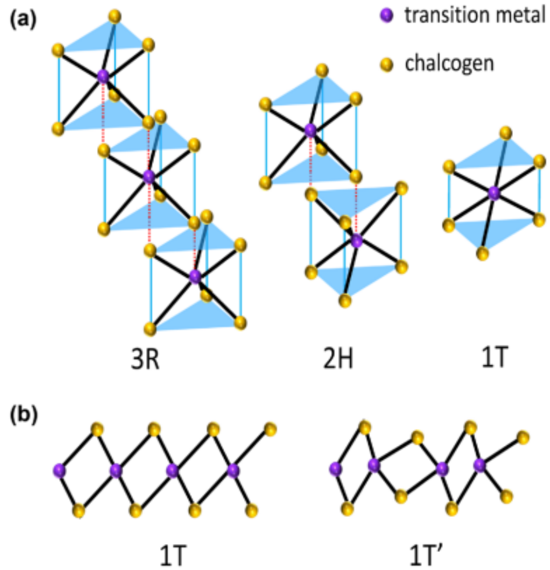

Figure 11. Three phases of MoS_2: $3R$, $2H$, and $1T$ (a). Top view of $1T$ and $1T'$ phases (b) [14].

Moreover, as MoS_2 is a kind of 2D material with almost one atom thickness, it can offer intriguing properties while placed in a bi- or multi-layer configuration. In fact, different layers of MoS_2 can be placed on top of each other with different angles to alter the properties of the material in the favor of different applications. For instance, twisted bi-layer $MoS2$ can be exploited to achieve dispersionless bands with strong orbital anisotropy owing to the destructive interference [15]. Besides, more layers with precisely engineered angles can be added to the structure to obtain the desired characteristics, which could not be acquired resorting to the conventional materials such as 3D heavy metals.

4 Summary & Outlook

The report provides an in-depth analysis of the development of computing devices the increasing importance of computing power and the increasing demand for energy-efficient technologies It also includes the energy consumption of current devices and the challenges of changing in developing energy-efficient solutions. As a potential solution for energy-efficient computing devices, the field of spin-orbitronics has mainly focused on the development of SOT-MRAM technology.

The report highlights the urgent need for energy-efficient devices to keep pace with the transition to green technologies. It examines spin-orbital science, including its basic concepts and required working mechanisms, with a special focus on the SOC of intra-atomic electrons. The research mainly emphasizes SOT-MRAM technology for data storage.

The implementation of SOT-MRAM is comprehensive, focusing on the application of SOT to modify the magnetic state of the free layer at the MTJ. The literature also builds on SOT-MRAM, with emphasis

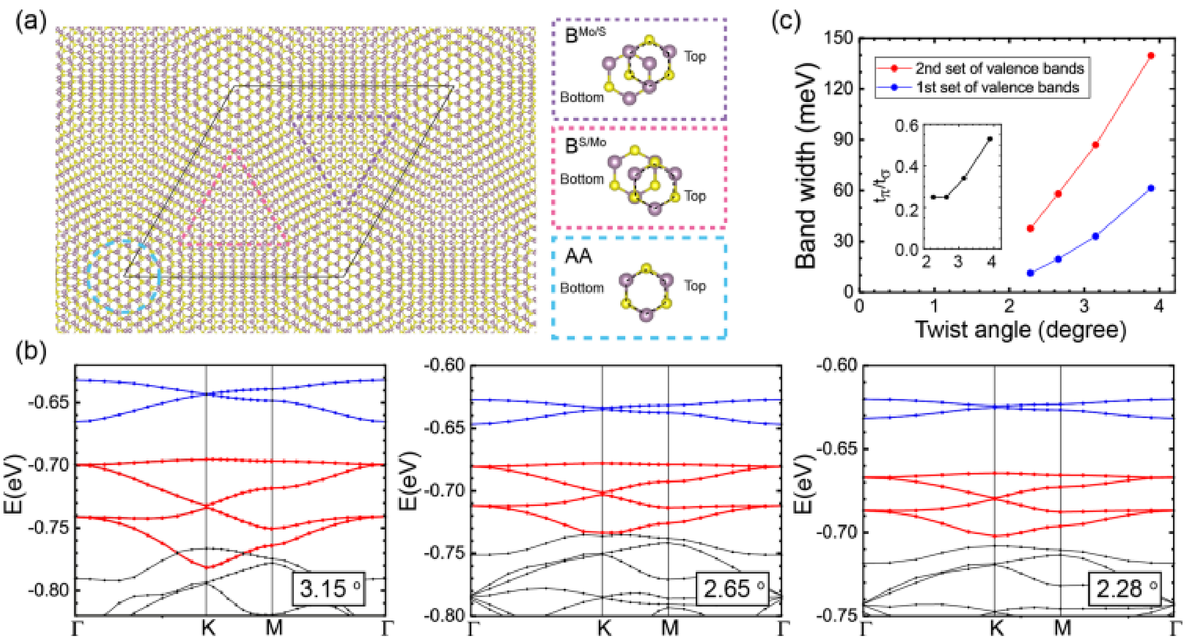

Figure 12. (a) Atomic structure of twister bi-layer MoS_2 at $\theta = 3.15°$. Local atomic arrangements of the three different regions in the moire unit cell are indicated in the right panels. The Mo (S) atoms are indicated with purple (yellow) balls. (b) Evolution of low-energy band structures at the top of the valence bands of twisted bi-layer MoS_2 with decreasing small twist angles. The first set and the second set of valence bands are highlighted with blue and red lines, respectively. (c) Evolution of the bandwidth of the first set and the second set of valence bands with decreasing twist angles. Inset: twist angle dependence of the ratio of the hopping amplitudes t_π and t_σ in the p_x–p_y honeycomb lattice [15].

made on unique characteristics of MRAM, such as the size of MRAM cells, scalability, and indestructibility of memory, which makes it suitable for a wide range of applications.

A comparison has been drawn between conventional materials used in the SOT-MRAM such as heavy metals and 2D materials. Specifically, TMDs are introduced as a class of 2D materials to tackle the issue of unwanted symmetries as well as the poor SOC coupling in the conventional materials. Among different TMDs, MoS_2 is proposed as a suitable candidate to replace conventional heavy metals in the devices functioning based on SOC due to its unique optical and magnetic characteristics.

Although 2D materials can be used to enhance the space, energy, and functionality of MRAMs, ongoing research is still being done on integrating 2D materials with conventional structures. Efficient fabrication and doping of so-called 2D materials remain a challenge and an open field of research. In addition to MRAMs, SOC devices can be used in variety of applications, such as sensors, spin transistors, quantum computing, between others.

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