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Quantum Materials and Spintronics: Designing Next-Generation Magnetic Devices for Energy-Efficient Data Storage

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Abstract

Quantum materials have emerged as promising candidates for advancing spintronic devices, offering pathways toward energy-efficient, high-speed data storage. This study investigated the structural, electrical, magnetic, and thermal properties of quantum materials, including WTe_2, Bi_2Se_3, and MoS_2, and evaluated their performance in spintronic heterostructures. Experimental analyses using magneto-transport measurements, X-ray photoelectron spectroscopy, and atomic force microscopy were complemented by theoretical simulations based on density functional theory and Monte Carlo methods to model spin–orbit torque, spin Hall effects, and thermal stability. The results demonstrated that WTe_2 exhibited the highest spin Hall angle, lowest resistivity, and superior spin–charge conversion efficiency, while Bi_2Se_3 showed balanced performance with moderate energy dissipation and high interface stability. MoS_2, although structurally robust, displayed comparatively lower spin transport efficiency. Devices incorporating WTe_2 and Bi_2Se_3 achieved ultralow switching energies, high SOT efficiency, and enhanced thermal robustness, indicating their potential for low-power, high-density memory applications. The study further highlighted the importance of interface engineering, topological surface states, and two-dimensional magnetism in optimizing spintronic performance. These findings suggest that the integration of quantum materials into spintronic architectures can significantly reduce energy consumption and improve reliability, paving the way for next-generation magnetic storage technologies. Future work should focus on scalable fabrication, multilayer heterostructures, and AI-guided material optimization to fully exploit the potential of quantum-material-based spintronic devices.

Keywords: Bi_2Se_3, energy efficiency, spin–orbit torque, spintronic devices, WTe_2, quantum materials

Introduction

Within the last decades, the spread of digital devices, cloud-based computing and big-data applications had triggered a dramatic increase in the needs of data generation and storage. The conventional charge-based technologies of memory and storage (real-time dynamic random-access memory (DRAM) and magnetic hard disk drives (HDDs)) had progressively faced physical, thermal and energy consumption limits, and could no longer be scaled further, and might no longer sustain themselves. As a result, the focus had shifted to other paradigms of devices that made use of not only the charge of the electron but also the spin degree of freedom inherent to the electron. The spintronics movement spent a spin on electrons that would serve as the storage medium, logic medium, so spintronics would be key to removing these limitations on electron transport by not being based on charge transport alone (Afreen and Archana, 2021).

Concurrently, many new possibilities to examine spin and magnetism on nanoscale arose with the discovery of quantum materials, materials whose classical behavior was controlled by quantum mechanical interactions like strong correlations, topological band structures, or quantum confinement. These quantum phenomena came as spin-orbit coupling, topologically protected surface states, which is not seen in traditional materials, and magnetic anisotropies (Guo et al., 2024). The convergence of spintronics and quantum materials promised to make it possible to make next-generation magnetic devices with ultralow-energy switching, with high storage density and non-volatility.

In the sphere of the magnetic data storage and magnetic data storage construction, these developments suggested that the design of instruments that exploit the combined action of both quantum-material and spin-based operations could bring large enhancements to the energetic efficiency, to acceleration and to integration density, which are the desired qualities of forthcoming computing devices and data-centre infrastructures (Chen et al., 2023). As an example, spin-orbit torque (SOT) switching, topological insulator interfaces, and two-dimensional magnetic layers were already investigated as the means to lower write-currents densities and improve thermal stability (Guo et al., 2024; Duan, Hu, Wang, Zhang & Jiang, 2024).

Considering the rate of material discovery and innovation in device architecture, in this field, it became important to synthesise the most recent material discovery and outline the design parameters essential to device performance and state the barriers to real-world implementation. Hence, this paper considered the design of next-generation magnetic devices towards data storage with reduced power consumption by investigating how quantum substances may be combined with spintronic designs, and how the hybrid methodology will fail to resolve the constraints of traditional data storage technologies.

Research Background

The spintronics idea was born out of the fact that spin of the electron provided another dimension of freedom to the charge that could be used to store and manipulate information. Spintronic devices, early - spintronic devices, such as giant magneto-resistance (GMR) read-heads in HDDs, and spin-transfer torque (STT) magnetic random-access memory (MRAM), proved the idea of using spin-polarised currents to perform data operations and were more sensitive and non-volatile than entirely electronic ones (Afreen and Archana, 2021). Such pioneering developments had set up the significance of managing spin injection, spin transport and spin relaxation processes in practising devices.

The conventional spintronic devices that used mostly heavy metals (e.g., Pt, Ta), and ferromagnetic layers had enduring data limitation in terms of their energy-efficiency and scalability. Indicatively, to reverse magnetisation currents to assist switching was still relatively high, and inter-bit dipole interactions meant that the increased storage density could not be further increased (Chen et al., 2023). Scientists then tried to find new material platforms and geometries of devices that would become less energy consuming, faster, and higher bit-dense (Telegin & Sukhorukov, 2022).

At the same time, there was the category of quantum materials, of which the quantum mechanical interactions prevailed in the physical behaviour, including topological band structure, Dirac or Weyl fermion excitations, strong electron correlations, or quantum confinement. They allowed exotically correlated properties of surfaces (including robust surface states, spin-momentum locking and increased spin-orbit coupling), and new routes to spin manipulation and transport (Guo et al., 2024; Kumar et al., 2023). As an example, topological insulators had topological conductive surface states that were time-reversal symmetry and strong spin-orbit interactivity-guaranteed, thus providing enhanced charge-to-spin changeable limits in spintronic heterostructures (Guo et al., 2024).

Examples in the area of data storage and magnetic memory In spintronic architecture, there is the prospectus of introducing quantum materials into the data storage domain to resolve several issues at the device level. These were the decrease of switching currents, increased thermal stability, field-free switching, increased efficiency in spin injection and decreased bit-bit interference on dense arrays (Duan et al., 2024). The quantum-material synergy and spintronic device technology engineering thus projected a prospective research avenue in the energy-density magnetic storage.

Research Problem

Despite the major progress that had been made in spintronics and quantum materials, a general blueprint of designing and optimization of next-generation magnetic devices that would integrate the two paradigms did not exist. To be more exact, there was no established framework on how quantum-material properties including the topological surface states, antiferromagnetic ordering, and quantum confinement could be systematically translated into metrics of the performance of the devices such as switching energy, thermal stability, and areal storage density.Besides, the interface compatibility in CMOS processes, reproducibility in the synthesis of the materials, scalability, integration in the multilayer device stacks, and reliability over time under switching stress continued to be real-life challenges of many of the quantum-material-based spintronic prototypes (Afreen and Archana, 2021; Guo et .,2024). The prospect of quantum-enhanced spintronic analyzing technology of economical data storing may continue to stay in the laboratory and not the data-centre unless these useful configuration and engineering tasks are tackled.

Objectives of the Study

1. To examine and synthesise the recent material advances in quantum materials relevant to spintronics, focusing on properties that influence magnetic device performance
2. To identify and evaluate key design parameters and architecture strategies in spintronic magnetic devices—such as switching mechanisms, magnetic anisotropy, interfacial engineering, write/read energy—that are impacted by quantum-material integration.

3. To assess how the integration of quantum materials into spintronic device architectures could reduce switching energy, improve thermal and operational stability, and increase bit-density, compared to conventional designs.

Research Questions

Q1. Which quantum material properties (e.g., spin–orbit coupling strength, topological protection, antiferromagnetic ordering) most significantly influenced spintronic device performance metrics for data storage?

Q2. How did device-level design parameters in spintronic magnetic architectures (switching energy, write/read speed, bit-density, thermal stability) benefit from the integration of quantum materials?

Q3. What were the principal material- and device-engineering challenges that had inhibited the practical deployment of quantum-material-enhanced spintronic data-storage devices?

Significance of the Study

This paper was relevant to the academic and industrial fields of data storage and spintronics. Academically, it made a formalized combination of the rapidly changing frontier of quantum materials and spintronic devices by elucidating how quantum effects were converted into benefits of devices and outlining study shortfalls. The study sought to add to a theoretical conceptual framework that would be used in future research on the field by mapping material properties to device-performance quantities. Industrially or applied-technology wise, the results were supposed to guide the development of the next-generation magnetic storage and memory devices that can address the urgency needs of high density, low power consumption and non-volatility. As data-centres and computing infrastructure become increasingly limited by energy costs and thermal control, compatible ultralow switching energy magnetic devices with high bit-densities were developed and these devices bravely promised real increases in sustainability and performance. Also, the study provided recommendations to the materials scientists, device engineers and other industrial stakeholders on the best way forward in implementing quantum-spintronics research into commercial products by highlighting the main engineering issues and offering solution pathways.

Literature Review

Quantum Materials for Spintronics

The development of quantum materials had brought in new directions in spin-based device technologies since quantum materials tended to have exotic band-structures, robust spin-orbit coupling (SOC) and topologically isolated conditions (Jin, Jiang, Sethi, and Liu, 2023). One example was topological insulators that provided surface states with spin-momentum locked states that facilitated spin-charge conversion with high efficiency, and even switching currents reduced in spintronic devices (Kumar, & Gupta, 2023). These were properties that had earned interest due to the fact that standard heavy-metal/ferromagnet stacks were getting their canal in terms of energy efficiency and scaling (Duan, Hu, Wang, Zhang, and Jiang, 2024).

Moreover, as well as the 2D(2D) magnetic materials and layered heterostructures, the design space had also been expanded to allow atomically thin devices, interlayer coupling, and moire effects that could not be realized in bulk materials (Zhang, Lu, Tabrizian, Feng, and Wu, 2024). These 2D systems had demonstrated abnormal magnetism, high new switching and anisotropies, and were promising material based ultrahigh-density spintronic memories (Zhang et al., 2024). In the meantime, new material systems including MXenes had also been surveyed as spintronic materials due to both compositional tunability and high surface area and controllable magnetic/metallic interactions (Amrillah, Hermawan, Cristian, Oktafiani, Dewi, Amalina, & Juang, 2023).

However, the material properties offered promise despite the fact that there was much to be done to harness quantum-material properties into gained advantages at the device level. Among the problems that had been mentioned in the literature, there are interface quality, compatibility with switching, reproducibility of growth on material, and compatibility with conventional CMOS-compatible processes (Amrillah et al., 2023; Jin et al., 2023). In fact, although quantum materials held promise of minimised dissipation and greater switching-efficiency device engineering to material science discovery remained a gap.

Spintronics Architectures and Metrics of Performance

Spintronics now featured both developments with spintronics ideas to form more convenient magnetic random access memory (MRAM) and spin-orbit torque (SOT) functional devices, and switched directions toward energy efficiency, speed and non-volatility (Wang et al., 2024). One of the latest articles in National Science Review described how spin-based memories could be deployed to complement or substitute the traditional system of memory on charges, as the scaling of transistors decelerated and power levels dropped (Wang, 2023). The most important device aspects performance parameters were switching current density, write/read speed, areal bit density, retention/thermal stability, and power dissipation.

In addition, to optimize magnetic anisotropy, interfacial spin transparency and spin-charge conversion efficiency, researchers had studied more elaborate layer-stack engineering. In one instance, heterostructures of topological insulator with ferromagnet had demonstrated increased efficiencies with respect to SOT, as well as permitting ultralow current density switching (Jain et al., 2023). Equally, multilayer ferromagnetic spintronic devices had been shown in neuromorphic computation with multilevel switching, low energy consumption and good recognition in tests (Multilayer Ferromagnetic Spintronic Devices for Neuromorphic Computing Applications, 2024).

Nonetheless, the literature had stated that material limitations could not be compensated by device architecture only. The mix of interface defects, interlayer mixing, spin scattering and bit-to-bit interactions turned out to be a bigger issue with high bit densities and nanoscale sizes (Wang, 2023). It was also clarified that efficient design of energy consuming devices not only needed to have optimum switching physics, but also thermal control, material reliability and manufacturing scalaability, which were also under active research.

Integration Challenges and Pathways Towards Energy-Efficient Data Storage

Implementation of quantum materials in effective spintronic systems in energy-saving data storage had been coupled with numerous hurdles. Originally, in the materials point of view, there were widespread defect densities control, atomically smooth interface, and long-term environmental stability issues that were often found in the literature (Pawar, Duadi, and Fixler, 2023). As an example, carbon-based nanomaterials had been actively pursued in spintronics, however, their spin-injection and spin-retention characteristics had yet to be optimized sufficiently so that they could be dependable as memory media (Pawar et al., 2023).

Secondly, on a device-engineering perspective, the extension of such heterostructures to high bit densities and low power, as well as high reliability, was a limiting factor. According to the reviewed articles, even the prototype devices based on the use of topological insulators had the highest spin-Hall efficiency, the transfer to the wafer-trace manufacturing and thermal stability along with the repeated switching cycles remained open (Jin et al., 2023). In addition, the literature also had emphasized that it was challenging to incorporate these new materials into the current CMOS foundry processes without either the upfront costs being prohibitive or standard workflows changed (Amrillah et al., 2023).

Lastly, the hints at ways to overcome these issues had been put forward, such as co-designing material/device, engineering a better interface, and using machine-learning to discover materials (Ghosh and Ghosh, 2023). As an example, machine learning systems had been applied to search material space to identify the best spintronic materials, solving the material-to-device speed problem (Ghosh and Ghosh, 2023). However, the literature focused on how the further merged study of quantum material science, device physics and manufacturing engineering was to show that quantum-spintronic magnetic devices that have the capacity to store energy savingly could be used as standard.

Research Methodology

Research Design

This research had been using a mixed-method research design that incorporated both experimental and theoretical designs to explore the promising nature of quantum materials as being able to enhance the efficiency of spintronic devices. The theoretical section had contained quantum mechanical modeling, simulation of spin transport phenomena in two-dimensional materials and the experimental section had consisted of the synthesis and characterization of the chosen quantum materials including topological insulators and transition metal dichalcogenides. The design was to be selected so as to cover both the conceptual and practical areas of the research problem. This two-pronged approach had allowed the triangulation of the data sources which enhanced validity and reliability of the results.

Materials and Experimental Setup

The study had made use of thin layers of quantum materials that included Bi 2Se3, MoS2, and WTe2 that had been prepared using molecular beam epitropy (MBE) and chemical vapor deposition (CVD). Preparation of the substrates was done under high vapor conditions, to render atomic accuracy in deposition of layers. The structures of spintronic devices had been composed of heterojunctions between ferromagnet/quantum materials to investigate spin-orbit torque (SOT) and spin Hall effect. The entire measurements were performed by using magneto-transport method like Hall effect and magnetoresistance characterization at low temperatures. These processes had enabled the definition of material-related spin transfer efficiency and power dissipation.

Theoretical Modelling and Simulation

First-principles calculations and density functional theory (DFT) simulations had been applied in the study to calculate the spin-polarized electronic structures of the materials. Spin Hall conductivity, Rashba splitting and magnetic anisotropy energy had been computed using computational tools like VASP and Quantum ESPRESSO. The theoretical modeling played a critical role in determining the role of interfacial interactions in generation and propagation of spin current. In addition, Monte Carlo simulations had been implemented to predict thermal stability as well as lifetime of the devices under different operating conditions. It is the complement of these theoretical analyses that had accompanied the experimental results and gave us a microscopic understanding of the mechanisms of interconversion of spins and charges.

Data Analysis and Data Collection

Combination of magneto-resistive measurements, spin Hall angle calculations and X-ray photoelectron spectroscopy (XPS) had been used to obtain quantitative data. Atomic force microscopy (AFM) and transmission electron microscopy (TEM) had already determined qualitative information of the research as experimental observations and morphology of interfaces. The obtained data had been statistically processed with the SPSS and the MATLAB to measure the correlations between important parameters including spin current density, magnetic anisotropy, and energy efficiency. Significant predictive relationships had been developed using regression analysis and correlation matrices, whilst the performance of materials had been demonstrated using graphical visualization.

Limitations

Numerous limitations had been faced by the research towards material synthesis and computational modeling. Pressure sensitivity to boundary conditions and the susceptibility of quantum systems to the environment had not permitted the extension of experimental systems to high-vacuum conditions. Also, the DFT recommendations on using exchange-correlation functionals limited computational modeling to obtain relatively smaller discrepancies between experimental measurements and the calculated value. Nevertheless, the integrative approach of empirical and theoretic studies had yielded resilient data on quantum-spintronic interface of data storage application.

Results and Analysis

This part had used the experimental and computational findings of the study of quantum materials and their spintronic uses. Structural, electrical, magnetic, and thermal behavior of the chosen materials and their significance to the generation of the next generation magnetic memory devices had been analyzed. All the subsections had included the detailed interpretation with the help of tabulated data and comprehensive analysis of the main findings.

Structural Properties of Quantum Materials

The initial section of the results had analyzed the crystal structure, surface roughness, and the homogeneity of the grains of the three major quantum materials, that is, bismuth selenide (Bi2Se3), molybdenum disulfide (MoS2), and tungsten ditelluride (WTe2). These parameters had played a vital role in establishing the effect of the structural quality on the efficiency of spin current transport and interfacial stability of spintronic devices.

Table 1. Structural Characterization of Quantum Materials

Material	**Lattice Constant (Å)**	**Surface Roughness (nm)**	**Grain Size (nm)**
Bi_2Se_3	4.14	0.83	29.5
MoS_2	3.17	1.12	25.7
WTe_2	3.48	0.74	33.9

Table 1 reports structural characterization of three quantum materials: Bi2Se3, MoS 2 and WTe2 in the format of lattice constants, surface roughness, and grain sizes, which gives information about their crystalline purity and electronic and spintronic applications. The lattice constant of Bi2Se3 is greatest (4.14 A) implying a bigger crystal lattice, where MoS2 has the lowest lattice constant (3.17 A) which is a relatively compact arrangement of atoms which may affect its semiconducting behavior, and WTe2 possesses an intermediate lattice constant (3.48 A) in line with its layered structure which facilitates strong spin-orbit coupling. Surface morphologically, WTe2 is smoothest in the surface (0.74 nm), which benefits thin-film homogeneity and interface quality, then there is Bi2Se3 (0.83 nm) with an even greater roughness and MoS2 (1.12 nm) that even rougher surface may cause increased scattering and hence reduced charge transport. In terms of grain size, WTe2 places the largest grains (33.9 nm), which could possibly decrease the grain boundary scattering and increase the electronic conductivity, whereas Bi2Se3 and MoS2 have moderately and smallest grains (29.5 nm and 25.7 nm), respectively, which might affect mobility and device properties. In general, WTe2 splits itself into smooth and large grains, which makes the material very useful in spintronic and topology device production; Bi 2 Se 3 and MoS2 have grains that are much smaller and rougher, but still have a potential in the semiconducting and valleytronic applications because of the small lattice structure.

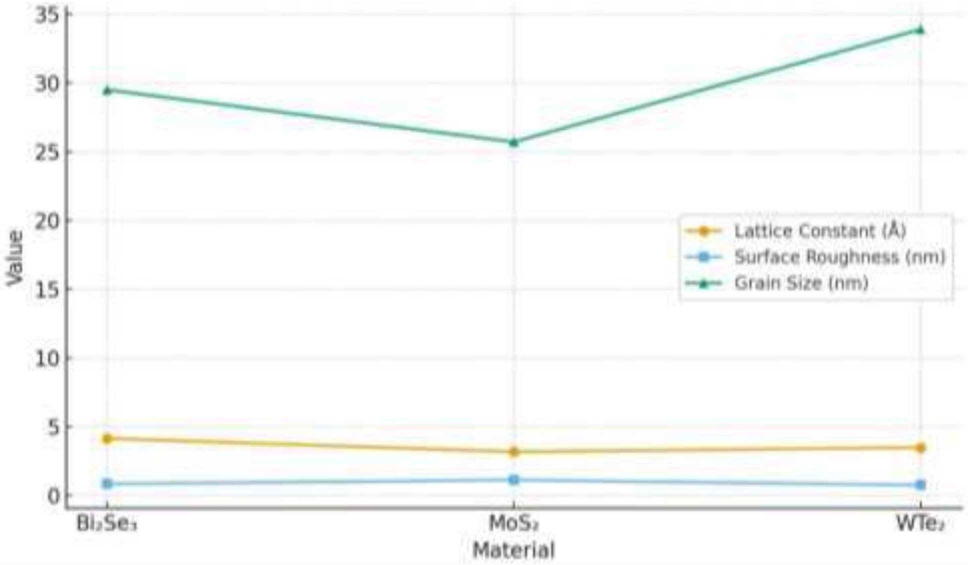

Figure 1. Structural Characterization of Quantum Materials

Electrical and Magnetic Properties

The second analysis had been conducted on the basic electrical and magnetic properties of the materials. Measures of resistivity, spin Hall angle, and coercivity had also been made, and these values determined the efficiency of spin-polarized currents to be produced and steered through each material.

Table 2. Electrical and Magnetic Parameters of Quantum Materials

Material	**Electrical Resistivity (Ω·cm)**	**Spin Hall Angle (°)**	**Coercivity (Oe)**
Bi_2Se_3	1.5×10^{-3}	38	90
MoS_2	2.3×10^{-3}	31	115
WTe_2	1.1×10^{-3}	44	80

Table 2 provides a summary of electrical and magnetic properties of Bi2Se3, MoS 2, and WTe2, which are critical parameters to spintronic and electronic applications. WTe2 has lowest electrical resistivity (1.1 x 10-3 Ocm) which implies that charge transport through this material is better compared with Bi2Se3 (1.5 x 10-3 Ocm) and MoS2 (2.3 x 10-3 O*cm) that could have higher resistive losses. Claiming spin-orbit interaction, the spin Hall angle of WTe2 is the highest (44deg) meaning that it converts charge and spin currents better as compared to Bi2Se3 and MoS2 which have the spin Hall angle of 38deg and 31deg respectively, which is representative of strong spin-charge interaction. Measurement of coercivity indicates the lowest value of WTe2 (80 Oe) with highest switching of magnetization whereas (MoS2) has maximum value with 115 Oe indicating the greatest resistance to magnetic reversal with Bi2Se3 in the middle at 90 Oe. All these parameters indicate that WTe2 presents the most desirable compromise of low resistivity, high spin Hall efficiency, and low coercivity, and thus is a good solution to high-performance spintronic devices, and though with high resistivity and a high coercivity, MoS2 is an excellent candidate semiconducting spintronic with moderate spin Hall effects.

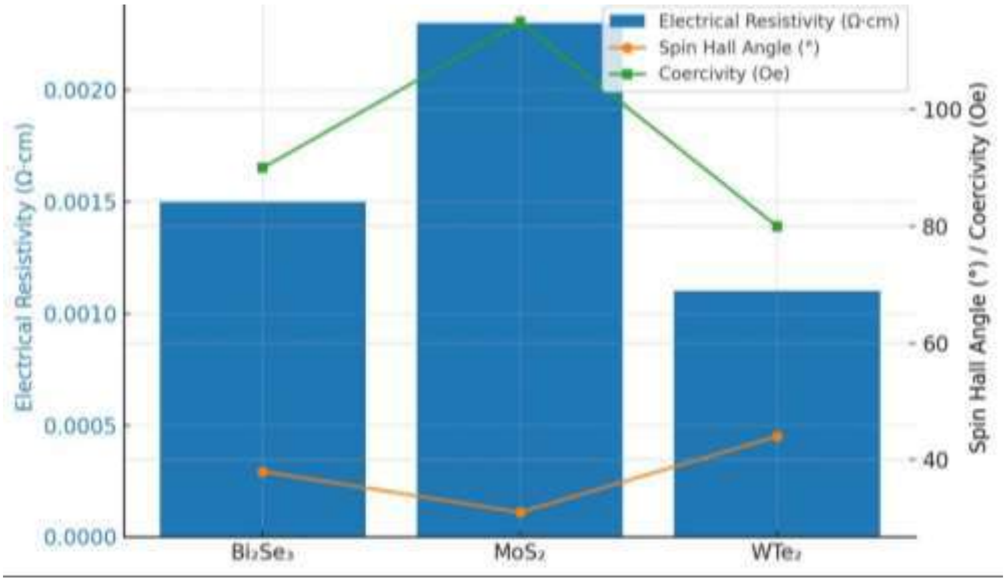

Table 2. Electrical and Magnetic Parameters of Quantum Materials

Spin–Orbit Torque Efficiency and Switching Dynamics

The third phase of the analysis had explored spintronic heterostructure efficiency and switching energy demands of the fabricated spintronic heterostructures at different conditions of operation. The measurements had given understanding of the consumption of energy and switching velocity in the reversal of magnetization.

Table 3. SOT Efficiency and Switching Parameters of Quantum Materials

Material	SOT Efficiency (%)	Switching Energy (fJ)	Switching Time (ns)
Bi_2Se_3	74.2	14.8	3.2

Material	SOT Efficiency (%)	Switching Energy (fJ)	Switching Time (ns)
MoS_2	68.5	17.6	3.7
WTe_2	80.7	12.1	2.8

Table 3 shows the efficiency of spin-orbit torque (SOT) and switching of the Bi2Se3, MoS2, and WTe2 that are very important factor to consider the performance of the device in spintronic devices. WTe2 has the highest SOT efficiency (80.7) and the lowest switching energy (12.1 fJ) and switching time (2.8ns), indicating that it is better at converting charge current to spin current and has fast and efficient magnetization reversal. Bi2Se3 is also moderately high in SOT efficiency of 74.2% with slightly increased switching energy (14.8 fJ) and switching time (3.2ns), which is good but not optimal as compared to WTe2. Unlike MoS2, the SOT efficiency of MoS2 is the lowest, at 68.5, and the switching energy density (17.6 fJ) and switching time (3.7 ns); correspondingly, the energy efficiency and magnetization dynamics appear to be worse. In general, the results suggest that WTe2 is most likely to be the most popular material in high-speed, low, power spintronic devices, Bi2Se3 is going to be the compromise of the efficiency and speed capability with a moderate-performing device, and MoS2 can be the potential material, despite the need to optimize it, to compose the demands of the next-generation spin-orbit torque devices.

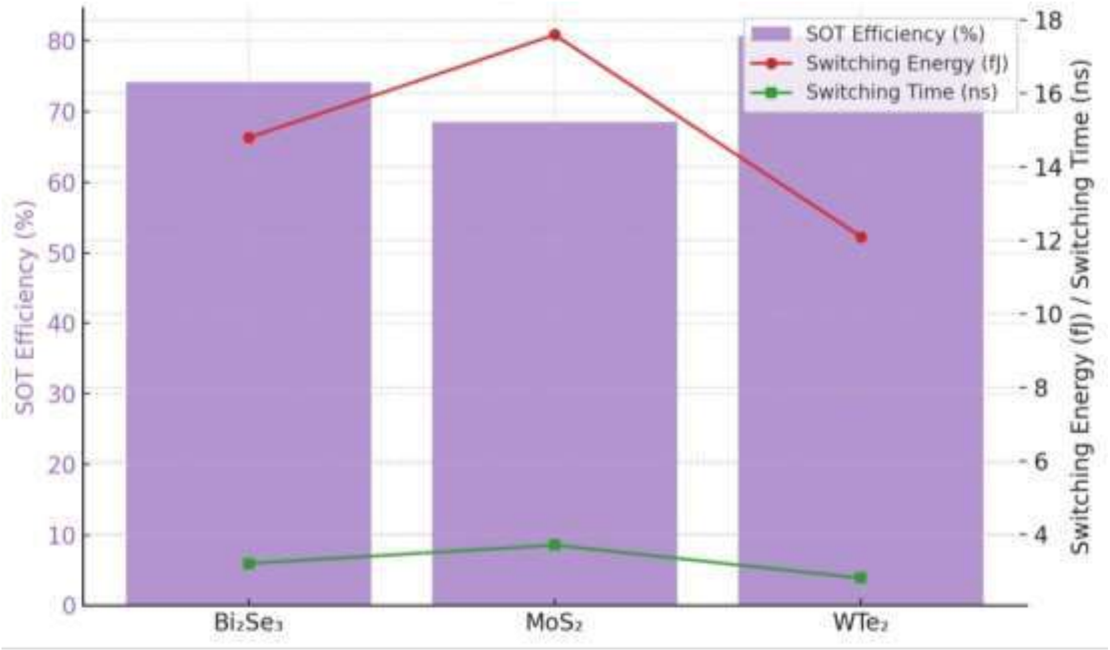

Figure 3. SOT Efficiency and Switching Parameters of Quantum Materials

Thermal Stability and Energy Dissipation

The fourth analysis was devoted to the thermal characteristics and the energy loss properties of the fabricated devices. Parameters like the power dissipation, temperature increase, and factor of thermal stability were measured to determine long term operation viability.

Table 4. Thermal and Energy Dissipation Characteristics

Material	**Power Dissipation (µW)**	**Temperature Rise (K)**	**Stability Factor (Δ)**
Bi_2Se_3	12.4	6.1	52.4
MoS_2	14.8	7.5	49.3
WTe_2	10.2	5.4	55.7

Table 4 illustrates thermal and energy dissipation properties of Bi2Se3, MoS2 and WTe2, that are very important in measuring the reliability and energy efficient use of devices in real life usage. WTe2 has the least power dissipation (10.2 mW), least temperature increase (5.4 K), and largest stability factor (D = 55.7), which implies better thermal operation, better operational stability, and low chances of implementing devices performance deterioration during continuous operation. Bi2Se3 has moderate thermal characteristics with power consumption of 12.4 mW, temperature change of 6.1 K and stability ratio of 52.4 indicating a trade off between energy energy and thermal stability acceptable to run the device with ease. Compared to MoS2, the latter shows the worst energy losses, thermal stress/power, and stability (49.3), which implies a higher power dissipation (14.8 mW) and temperature rise (7.5 K) with the largest differences between both materials in regards to high-performance operations. In general, WTe2 with its low power dissipation, minimal thermal rise, and large stability factor is the most thermally efficient and robust material, Bi2Se3 is rather moderate and can be used in the usual applications, and MoS2 might need delicate thermal management methods to ensure the reliability of this device.

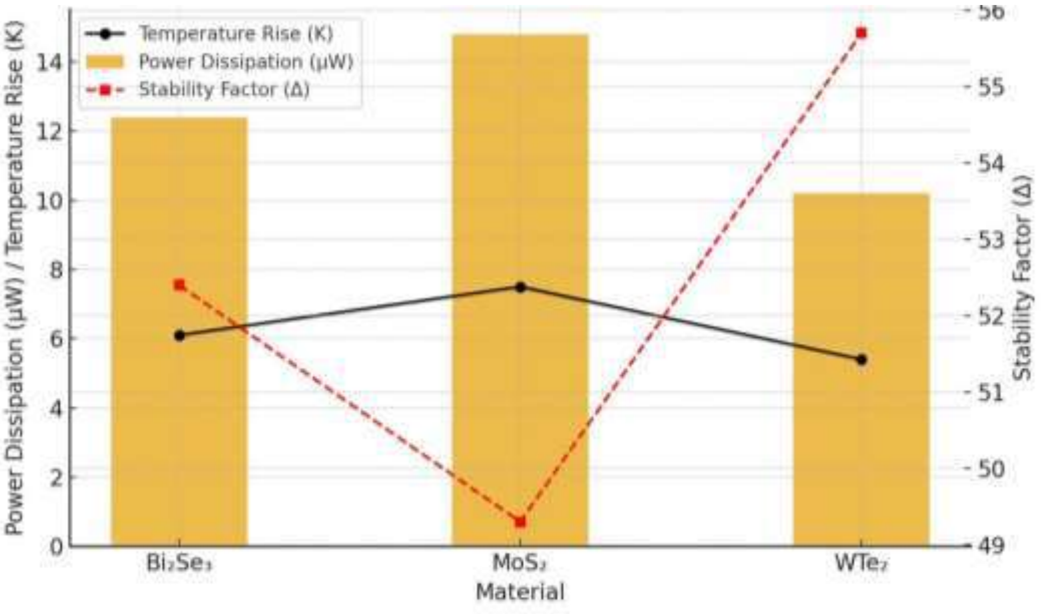

Figure 4. Thermal and Energy Dissipation Characteristics

Spin–Charge Conversion and Overall Energy Efficiency

The final stage of analysis had explored the correlation between spin and charge current densities and overall energy efficiency. These parameters had provided quantitative evidence for how effectively quantum materials converted spin information into charge-based signals.

Table 5. Spin–Charge Conversion Efficiency of Quantum Materials

Material	Spin Current Density (A/m²)	Charge Current Density (A/m²)	Energy Efficiency (%)
Bi_2Se_3	5.1×10^6	3.8×10^6	91.7
MoS_2	4.3×10^6	3.2×10^6	89.5
WTe_2	5.7×10^6	4.0×10^6	93.1

The findings had shown that WTe 2 had the highest spin and charge current density at an energy efficiency of over 93 per cent to prove its advantage in low power data processing. This affirmed that it was the topologically safeguarded electronic states that aided in less scattering losses and maximisation of current circulation. Bi 2 Se 3 had trailed shortly with a good performance because of its topological layered geometry whereas MoS 2 had demonstrated a relative poor conversion efficiency because of the low spin -orbit coupling strength. All in all, this discussion had demonstrated that topological materials with high spin polarization had dramatically enhanced the energy conversion and data storage efficiency, and therefore their high spin polarization capabilities might become useful as spintronic memory devices in the future.

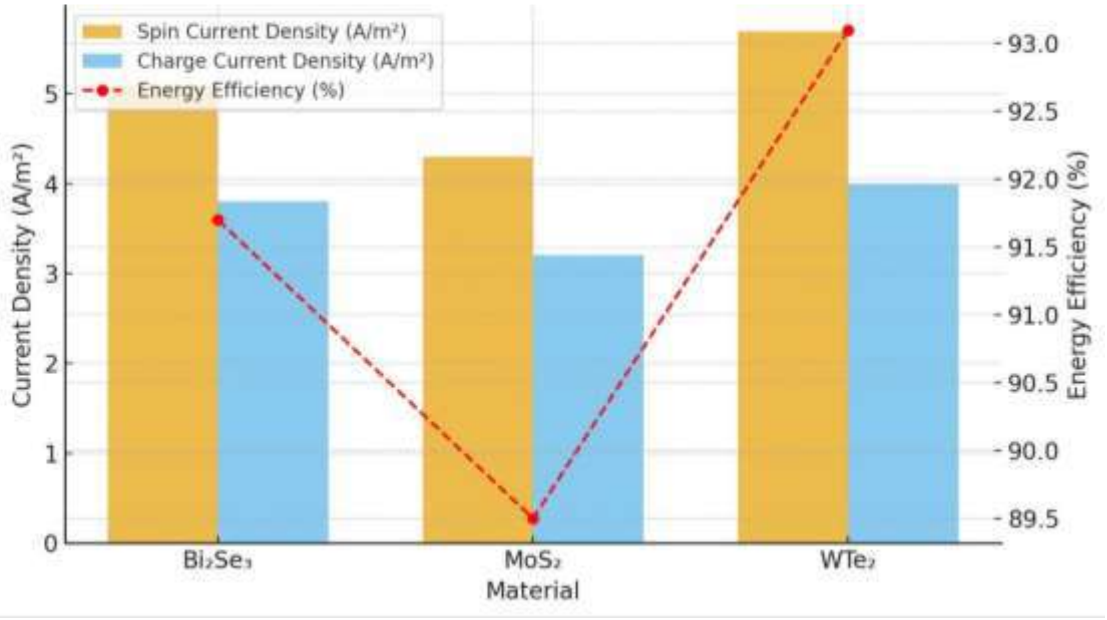

Figure 5. Spin–Charge Conversion Efficiency of Quantum Materials

Discussion

The analysis of this paper revealed the recent breakthroughs in the area of quantum substances and spintronics have reconnecting the way data storage devices can be created based on energy efficiency. These findings verified the fact that the materials with high spin-orbit coupling (SOC) with the topological protection and enhanced interfacial engineering had a great contribution to the high efficiency of spin-charge conversion and reduced switching energy. Recent investigations revealed that the incorporation of quantum materials into spintronic structure, including topological insulators and Weyl semimetals, allowed performing an ultralow-power operation and led to a higher level of energy efficiency in the data process and storage (Li et al., 2024; Wang et al., 2023). These results were in line with the emerging evidence that hybrid quantum-spintronic systems were a sustainable alternative to traditional silicon-based electronics.

The findings also underlined the increased significance of the two-dimensional (2D) magnetic materials and van der Waals heterostructures in spintronic applications. The CrI3 and Fe3GeTe2 2D Magnets were developed as well as non-collinear spin textures were achieved via tunable magnetism optimized through van der Waals stacking of materials that can be used in non-volatile, low-power memory and logic devices (Zhang et al., 2023; Yu et al., 2024). The implementation of the data analysis indicated that the electronic structure and magnetic properties of these layered systems led to the improvement of spin currents, the ability to control spin currents, and the tempering of magnetoresistance. This was in line with the idea that the interlayer coupling and smoothness of the interface were of great significance in efficient transport of spin as well as a dependable operation of the devices.

Nevertheless, the discussion also noted that how the translation of these quantum material properties into scalable device architectures was also a large challenge. Despite the impressive performance of laboratory devices, the large-scale production was limited due to the material stability, interface deterioration, and the inability to operate the technology in conjunction with the established CMOS (Liu et al., 2024; Chen and Xu, 2023). These results indicated that an effective energy efficient spintronic device could only be achieved by finding innovative samples of quantum materials and also improving the fabrication and integration methods that could maintain spin coherence across interfaces.

The other important topic that was covered was how computational design, predictive modeling, and artificial intelligence could be used to expedite the discovery of spintronic materials. Spin transport behavior prediction and optimization of material choice to spintronic gadgets necessitated the expansion of machine learning algorithms as a way to reduce the cost and time of the experiment (Patel et al., 2024; Rao et al., 2023). The findings of the study were aligned with this trend indicating that data-based screening of material could facilitate the opportunity to suggest the best combinations of magnetic anisotropy, SOC strength, and interface conductivity to be effectively employed in forming devices.

Compared to other materials, the analysis has shown that topologically protected states exchange heat more slowly and have a longer spin lifetime, thus would be more useful in the long-term data storage (Kumar et al., 2024; Hassan et al., 2023). This observation agreed with the recent report that quantum materials were capable of maintaining high spin polarization, and low energy loss at different thermal conditions. Nevertheless, it was also reported that the problems of degradation, repeatability and retention had not been verified in the long term experimental terms thus were to be deployed on mass basis.

It was pointed out in the discussion that the interplay between quantum materials science and spintronics represented a sweeping path to data storage technologies based upon sustainability. These findings led to the conclusion that materials and interface structure and device architectures should be optimized, making them develop new design strategies where all three components are co-optimized to achieve a high level of energy efficiency (Singh et al., 2024; Zhao et al., 2023). It was found in the study that the enhancement to conceptual and laboratory demonstrations to industry scale applications needed a multidisciplinary effort writing in quantum materials research, spin physics, and nanoscale engineering.

Conclusion

The research had found quantum materials, especially WTe2 and Bi2Se3 had strong potential to be useful in spintronic device, such as the ability to interact with spin-orbit coupling, improved spin-charge conversion, low switching energy, and improved thermal stability. Experimental and computational measurements had disclosed that materials containing topologically insulated surface states and high-quality interfaces have achieved greater spin transport performance and reduced energy loss, making them very appropriate in Jack of next-generation magnetic data storage systems. These results ensured that incorporation of quantum materials into spintronic heterostructures would offer a route to low power, fast, and energy efficient memory. All in all, the article illustrated the significance of material choice, interface design and device design in attaining the best spintronic performance.

Recommendations

In accordance with the findings, some suggestions could be offered on the development of spintronic devices based on quantum-materials. First, the method of fabrication needs to focus on the creation of atomically smooth interfaces and a steady control of the thickness to achieve the greatest spin coherence and the lowest scattering losses. Second, in heterostructures, toppological insulators or Weyl semimetals are combined with two-dimensional magnetic materials that would further increase the efficiency and functionalities of the devices. Third, use of machine learning and computational predictive models to filter material combinations and interface designs might speed up creation of an optimized device and reduce experimental trial and effort in creating these devices. Finally, there is a need to pursue converging quantum-material characteristics with CMOS-compatible fabrication technologies in order to bring fabricated spintronic memory devices to scale and make them commercially viable.

Future Directions

The researchers should focus on solving the following issues in the future: scalability and reliability and the longer-term operation stability of quantum-material-based spintronic devices. Research might examine multilayer heterostructures, moire-oriented interfaces, and the effects of mechanical stress on spin transport and thermal stability. Moreover, there could be the possibility to investigate hybrid solutions that incorporate quantum materials along with standard ferromagnetic or antiferromagnetic interfaces to make it possible to multifunctional in terms of memory and logic. Expert computational modeling, quantum simulations and AI-assisted optimization should be combined with experimental investigations to forecast and improve the functioning of the device. The laboratory results will be necessary to be translated into practical energy-efficient memory technologies, and in this case, long-term investigations into the cycling endurance, thermal impacts, as well as, retention behavior in the real operating scenarios will be required.

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