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Spintronics: Exploring Efficient Spin Current Generation in Topological and 2D Materials

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Abstract. Spintronics offers a transformative paradigm for next-generation, energy-efficient information technology by utilizing the intrinsic spin of electrons alongside their charge. While conventional spintronic devices have demonstrated ultrafast switching and non-volatility, their reliance on thick metallic layers limits ultra-dense integration. This paper reviews the emerging frontiers of spin current generation, focusing on the integration of topological insulators, two-dimensional (2D) materials, and quantum magnets. We examine the mechanisms of spin-orbit torque (SOT) and tunneling magnetoresistance (TMR), highlighting how reduced dimensionality and strong spin-orbit coupling in van der Waals heterostructures enable highly efficient spin manipulation. Furthermore, we address the persistent challenges of interfacial scattering and the ambiguity in defining spin currents in spin-orbit coupled systems. To resolve this, we emphasize the theoretical framework of the Spin Accumulation Coefficient (SAC), which provides a unified, first-principles approach to quantifying spin responses. By bridging theoretical modeling with recent experimental demonstrations of robust spin accumulation in materials like Bi2Te3 and MoS2, this study outlines a comprehensive pathway toward scalable, low-dissipation spintronic architectures.

Keywords: Spintronics, Spin-Orbit Torque, Topological Materials, Two-Dimensional Materials, Spin Accumulation Coefficient

1. Introduction

Spintronics (spin electronics), a new frontier of electronics, relies on electron spin, in addition to its charge, for information storage and processing. Compared with conventional charge-based electronics, spintronic devices exhibit high speed, low power and non-volatility. For example, on 300 mm wafers, Spin-Orbit Torque (SOT) MRAM has achieved switching as fast as ~210 ps with write energies as low as a few hundred picojoules [1]. Furthermore, highly scaled SOT-MRAM prototypes exhibit switching energies less than 100 fJ/bit, and endurance better than 10^15 cycles, implying practically unlimited device lifetime [2]. Another study using Au0.25Pt0.75 as the spin Hall metal achieved ultrafast switching down to 200 ps and exhibited write energies less than 1 fJ, when the write error rate requirements are relaxed [3]. Furthermore, in magnetic sensing, tunneling magnetoresistance (TMR) using MgO barrier can achieve giant magnetoresistance (GMR) ratios of greater than 600% at room temperature [4], which is much higher than the typical GMR ratio (~ 6–10%) of the conventional GMR sensors. These quantitative improvements are the basis for using spintronic devices in magnetic sensors and magnetic random-access memory (MRAM) to achieve high endurance and ultrafast performance. Although these are significant achievements, current spintronic devices still exhibit limited scaling because many of their structures often incorporate relatively thick metallic layers or full three-dimensional heterostructures which are not suitable for the next generation of extremely dense integration. It is thus of great interest to investigate two dimensional (2D) materials. As they are intrinsically atomically thin, with reduced dimensionality and strong spin-orbit coupling, 2D materials allow for highly efficient spin generation and manipulation in much smaller device footprints.

Future spintronics is about quantum, topological, and low-dimensional materials for spin generation and control [5]. New frameworks such as the spin accumulation coefficient (SAC) [6,7] provide unified theoretical description of spin responses, first-principles modeling, and experiment. They are already enabling new technologies, such as magnetic sensors and MRAM with non-volatility (i.e., data is retained without power), extremely high endurance, and extremely fast write/read.

2. Background

With a growing demand for low-power and high-density, high-speed information technology, the efficient generation and control of spin-current has become a fundamental question in spintronics. On the one hand, energy dissipation in conventional CMOS circuits is scaling-dependent, and global data centers already consume ~1–1.5% of global electricity, expected to increase up to ~13% by 2030 without any device-efficiency breakthroughs [8]. On the other hand, spintronic devices are able to merge the advantage of non-volatility and the advantage of low switching energy. For instance, perturbative modeling of voltage-controlled topological spin switch (vTOPSS), predicts energy dissipation per bit up to ~70 times lower than spintronic counterpart and below current state-of-the-art CMOS, with switching energy at sub-10 attojoule level [9]. Even more recent experimental results, achieved on layered diluted magnetic semiconductors, such as on V-doped WSe2, revealed electrical spin-flip switching at room temperature, with ultralow critical switching current densities (~10–1 A/cm2), and picowatt energy consumption [10]. In this context, this article will highlight particularly the recent combination of spintronics with topological materials, two-dimensional (2D) systems and quantum magnets, paving the way for novel devices and quantum functionalities. As a demonstrative case, we take the work by Nigmatulin, Lado and Sun [11] on a van der Waals heterostructure made of a quantum spin Hall (QSH) insulator and a spin-spiral magnet, where a 1T′-WTe2 layer is hosting spin-momentum-locked helical edge states, locally disrupted by the overlying 2D spin-spiral magnetic texture through exchange coupling.

Topological edge states for magnetically active van der Waals layers: Perspective on Spintronics and Quantum Materials. The proliferation of topological states of matter in recent years has led to a new wave of research focusing on physics at interfaces between topological and magnetically active van der Waals layers. In this perspective paper, we argue that such junction systems can be described by a minimal model Hamiltonian of the form H = HQSH + HJ + Hdis, where each of the three terms models an essential physical mechanism. HQSH is the intrinsic Hamiltonian of the quantum spin Hall system, which is responsible for the band inversion and spin–orbit interaction of the edge states. The exchange term HJ couples these itinerant electrons to a set of local magnetic moments, which breaks the time-reversal symmetry and opens energy gaps in their spectrum, but can also lead to nontrivial magnetic configurations such as spin spirals. In Figure 1, it has been shown that Hdis models the various sources of imperfection (impurities, interface roughness, scattering centers, etc.) that are present in realistic systems and which affect the transport properties. We illustrate these ideas through a review of recent studies on the coupling of topological edge states to magnetically active, two-dimensional layers, and show how varying the spiral wave vector q can open a transport gap in the edge conduction channels. This provides an electrical read-out of the non-collinear magnetic order via the modulation of spin currents. This new form of synergy between spintronics and topological and quantum materials will open the door to low-dissipation spin logic and possibly quantum devices.)

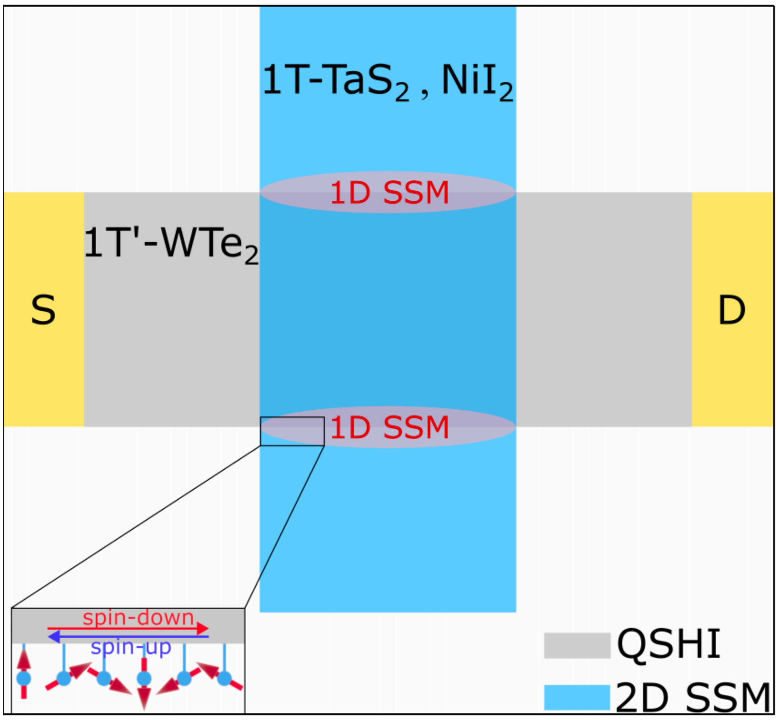

Figure 1. Schematic of the van der Waals heterostructure formed by a QSHI (1T′-WTe2 monolayer) and a 2D spin-spiral magnet (1T-TaS2 or NiI2 monolayer) Schematic of the van der Waals heterostructure formed by a QSHI (1T′-WTe2 monolayer) and a 2D spin-spiral magnet (1T-TaS2 or NiI2 monolayer)

The Figure-2 below has visualized the band structure of a QSH/spin-spiral magnet heterostructure for different spiral wave vectors q. The One-dimensional spin spirals are formed on the edges of a 1T′-WTe2 flake due to the exchange proximity effect. The source (S) and drain (D) electrodes pass a current through the channel. In the inset, the local magnetic moments are shown with red arrows, having an angle of π/3 between neighboring sites (q = 1/6), and the spin-polarized edges are represented by thin horizontal blue and red arrows.

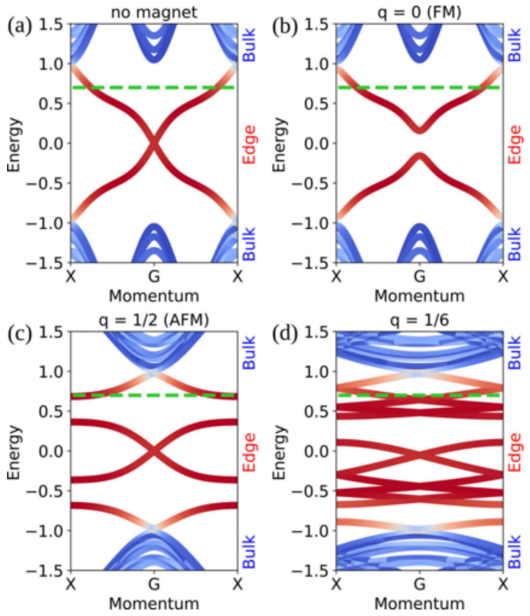

Figure 2. Band structure of a QSH/spin-spiral magnet heterostructure for different spiral wave vectors q. The helical edge states (red/blue) interact with the noncollinear magnetic texture, producing a tunable transport gap. Adapted from F. Nigmatulin, J. L. Lado, and Z. Sun, Phys. Rev. B 112, 024430 (2025) [11]. Copyright 2025 American Physical Society

3. Main content

This paper seeks to show an overview of the research workflow for studying how to synthesize and control highly efficient spin currents on diverse material platforms. For Material Design, spin–orbit coupling (SOC) effects and nontrivial topological features can be identified based on first-principles calculations and symmetry analysis, which are expected to introduce large intrinsic spin Hall conductivity or interfacial Edelstein response [12]. In Material Synthesis, high-quality thin films and two-dimensional layers can be obtained via MBE, CVD, or exfoliation. For example, growth quality and interface sharpness can have a large impact on both spin-charge conversion and SOT efficiency; an extremely large SOT efficiency on topological-insulator/ferromagnet interfaces was found when the interfacial disorder was minimized [13]. For Characterization, structural quality and electronic/magnetic response can be calibrated via XRD, TEM, magnetometry, and transport measurements. These characterizations can measure the spin Hall angle and spin diffusion length as well as the torque efficiencies, which is quantitative for evaluating candidate materials. For Mechanism Research, competing effects such as bulk SHE, Rashba–Edelstein effect, spin pumping, and magnon-mediated transport must be disentangling, which is particularly challenging based on comprehensive reviews that discuss challenges of distinguishing Berry-curvature contributions from extrinsic scattering in real materials [14]. Finally, for Theory & Modeling, tight-binding simulation and Berry-phase calculations can help connect experimental observations to the microscopic mechanism. These models can be used to predict device-level responses and guide subsequent mechanism research and material design in a design–test–understand loop.

To enable systematic exploration of spin current generation in low-dimensional and topological materials, this project aims at several important goals. First, one must understand the basic principles behind different types of spin generation, including the Spin Hall Effect (SHE), spin injection, and spin pumping. Next, one must identify promising materials and heterostructures with strong spin generation efficiencies. Then, another important goal is to discover and apply the concept of Spin Accumulation Coefficient (SAC) to spintronics modeling. Finally, one must construct simplified computational models by using Python or other established educational simulation platforms to help illustrate and quantify basic spin transport phenomena. The implementation of these goals follows a step-by-step research plan. First, initial investigations will be directed at gaining a grasp of key concepts in spintronics, spin current, and the spin Hall effect by reviewing fundamental literature. Next, the research will investigate scientific literature from e.g. the past 5 years that describes spin current generation in topological materials, and will classify these methodologies and their efficiencies. Next, computational models will be constructed to simulate spin alignment and transport. Finally, these studies will be synthesized into a review of materials and their corresponding SAC values.

4. Challenges

Several experimentally distinct mechanisms have been employed recently to generate and detect spin-polarized currents. Electrical spin injection from ferromagnetic (FM) contacts to nonmagnetic channels in lateral spin valves generates nonequilibrium spin accumulation, which can be detected nonlocally [15]. Alternatively, spin currents can be created in materials with strong spin-orbit coupling that convert electrical charge currents into transverse spin currents via the spin Hall effect (SHE); spin moments created by such a spin current create spin-orbit torques (SOT) that have been used to switch nanomagnets, such as using the "giant" SHE in β-Ta [16] and the large torques generated via the topological-insulator surface states [13]. These methods are complemented by dynamical methods that produce spin currents: a precessing FM can pump spin into conductors adjacent to the FM (spin-pumping), which can be detected as enhanced damping and via dc voltages induced by a spin current converted via inverse-SHE detectors [17,18]. Finally, spin currents can be driven by thermal gradients via the spin Seebeck effect, which generates macroscopic voltages detected by inverse SHE in an attached heavy metal [19]. These experimentally distinct but complemental methods of electrical injection and spin current generation via SHE/SOT, spin pumping, and spin Seebeck, along with the associated detection methods, constitute a toolbox to generate and interrogate spin currents for diverse material platforms, from conventional metals to topological insulators to 2D magnets, that we will review in this article.

Recent progress has been made for spintronics devices such as magnetic tunnel junctions (MTJs) and racetrack memories. For example, Scheike et al. achieved a record TMR of 631% in CoFe/MgO/CoFe(001) MTJs at room temperature by interfacial engineering and an ultrathin magnesium insertion to suppress defect scattering [20]. Another line of work focuses on the first-principles design of doped electrode MTJs: for example, Tanaka et al. show that electrodes with appropriate momentum-dependent spin splitting can result in finite TMR even though nontrivial regions exist in the usual spin-resolved density of states of nonmagnetic electrodes [21]. Nonetheless, there remain significant challenges:

Low efficiency methods such as spin injection through interface, a well-known approach, are poorly efficient because of scattering and interface mismatch. Indeed, Hirohata et al [22]. reviewed the present status of spin injection efficiency η, which is degraded by interfacial spin-flip scattering, spin memory loss, and impedance mismatch between layers.Ambiguity of definition spin current is not conserved when spin–orbit coupling is present, hence its measurement or theoretical calculation is sometimes not well-defined. In fact, Linder [23] explains the issues with definition in the presence of interfacial spin currents and spin nonconservation in hybrid structures. Material issues: materials with the desirable properties of strong spin–orbit coupling, high spin coherence length, and adequate crystallinity are in short supply and hard to manipulate. Therefore, it is necessary to separate the ide - al material palette from the actual material synthesis as reviewed in [24] – th SOT-based spintronics.

To resolve the ambiguity in the definition of spin currents in spin-orbit coupled systems, theoretical works have suggested the spin accumulation coefficient (SAC) [6]. SAC circumvents the non-conservation of spin current by directly measuring the resulting spin accumulation from an applied electric field. It defines a unique observable that can be computed from ab initio calculations via Wannier interpolation to bridge the gap between theory and experiment in spin-charge conversion [7]. While not yet directly measured by that name in MoS2 or Bi2Te3, experiments such as Li et al. have realized very large spin accumulation and high efficiency charge to spin and spin to charge conversion in Bi2Te3 with a BN/Al2O3 barrier, resulting in high polarization of the surface states [25]. Xiao et al. also show that MoS2 monolayers have a valley contrasting spin splitting at the valence band edge from inversion symmetry breaking and strong SOC; as theory suggests, this is ideal for large spin accumulations (or spin-valley accumulations) from applied electric fields or currents [26]. These results are encouraging for completing the SAC or related quantitative measurement in real 2D/topological materials. Figure 3 shows the electrically detected spin accumulation and charge to spin-/spin-to-charge-conversion in a Bi2Te3 device with a BN/Al2O3 hybrid tunnel barrier. The device layout and detector voltage as a function of bias current clearly establish current-induced spin polarization in the topological surface states.

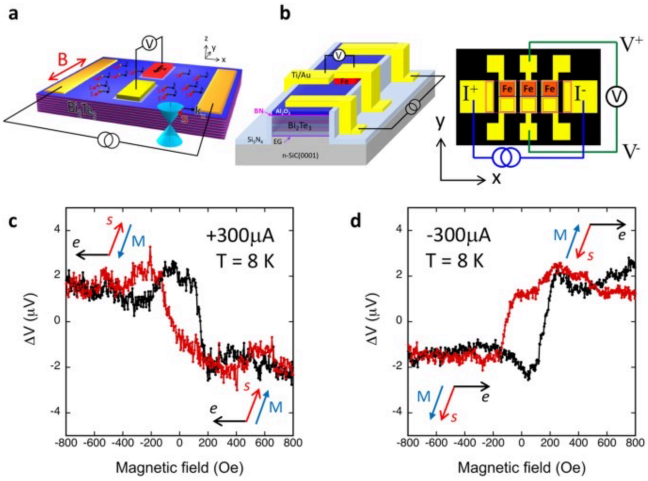

Figure 3. Electrically detected spin accumulation and charge-to-spin / spin-to-charge conversion in a Bi2Te3 device using a BN/Al2O3 hybrid tunnel barrier. The device layout and detector voltages under different bias currents clearly demonstrate spin polarization induced by current flow in the topological surface states. Reprinted from C. H. Li et al., Sci. Rep. 8, 15832 (2018) [25]. DOI: 10.1038/s41598-018-28547-y

5. Conclusion

The enhanced efficiency in spintronic devices is attributed to the progress on spin–orbit torque (SOT) switching, perpendicular magnetic tunnel junctions (MTJs), spin-pumping, and spin injection techniques [22,5]. With the development of spintronic materials and devices, it is imperative to know how symmetry, dimensionality, and interface engineering rules govern spin transport and spin-charge conversion efficiency. This research report has explored the progress on spintronics from the first achieved spin injection and spin Hall effect–driven current generation to the integration of functional magnetic quantum, topological, and two-dimensional materials. We further clarified the simultaneous contribution of multiple transition metal d orbitals and interfacial skew scattering mechanism in the spin Hall effect and spin-charge conversion efficiency in topological insulators, vdW magnets, and semimetals. Moreover, we explored the interfacial spin–orbit coupling–driven spin-charge conversion in novel two-dimensional materials and clarified the mechanism on how spin-pumping efficiency depends on spin current. The author has also introduced the quantum mechanical counterpart of spin current, spin accumulation, and developed the unique spin accumulation coefficient (SAC) as a theoretical framework to understand the fundamental spin physics in spin–orbit-coupled systems. This review on spin-charge conversion in van der Waals (vdW) MoS2 and spin accumulation properties in p-doped Bi2Te3 demonstrates the great potential of achieving robust spin accumulation and charge–spin conversion in real materials [6,7,25,26]. Taken together, this research report summarizes the progress and future directions on spintronic materials and devices.

Looking forward, future spintronics will likely focus on quantitative modeling, materials innovation, and scalable integration. The SAC framework is expected to become a standardized descriptor linking ab initio calculations with measurable spin responses, thus bridging theory and experiment [7]. Continued exploration of van der Waals magnets, antiferromagnetic spintronics, and topological heterostructures could enable room-temperature, low-power operation and neuromorphic functionality [10,11,27].

Achieving these goals will require controlling interfacial spin–orbit coupling and maintaining coherence in low-dimensional systems—areas where experimental precision and materials design remain limiting factors. In the long term, coupling spintronic systems with quantum computing, opto-spintronic, and energy-harvesting architectures may lead to multifunctional devices that transcend the boundaries between logic, memory, and sensing [5,22]. Interdisciplinary collaboration between materials theory, nanofabrication, and computational data science will be key to realizing this next generation of spin-based electronics.

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