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ABSTRACT

Materials for Spin-Orbitronics

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Abstract

In the thesis *Materials for Spin-Orbitronics*, I summarize my post doctorate research activities at the Center for Spintronics, Superconductivity, and Surface Science (C4S/TUCN), emphasizing a novel research direction I established: spin-orbitronics. This field utilizes spin-orbit coupling in nonmagnetic materials for efficient generation, detection, and manipulation of spin currents, crucial for electrically controlling chiral magnetic textures such as domain walls and skyrmions in ultrathin ferromagnetic films. My research focuses on optimizing materials and interfaces to enhance device performance, reliability, and efficiency for applications in spintronic memory, logic, and advanced computing architectures.

In ultrathin films, the properties traditionally associated with bulk materials are substantially altered due to pronounced surface and interfacial effects. At atomic-scale thicknesses, surface atoms assume a dominant role, significantly modifying characteristics such as magnetic anisotropy, damping, and interfacial Dzyaloshinskii–Moriya interaction. These properties become highly sensitive to interface quality, atomic arrangement, and the presence of structural defects, displaying intricate relationships that demand accurate control and analysis. Recognizing the importance of precise interface engineering and material deposition quality, I designed and supervised the construction of a specialized hybrid ultra-high vacuum deposition system at C4S/TUCN, combining magnetron sputtering and electron-beam evaporation techniques (`https://c4s.utcluj.ro/facilities.html`). This system provides exceptional control over interface composition and structure, thereby enabling the tailored fabrication of spintronic heterostructures with enhanced performance and reliability.

The manuscript is organized into two primary sections. The first section, *Scientific Achievements*, presents fundamental concepts in spin-orbitronics, identifying the optimal heavy-metal (HM)/ferromagnet (FM)/capping-layer (CL) structure for efficient spin-orbit torque-driven motion of chiral magnetic domain walls and skyrmions. Essential criteria for effective functionality include strong perpendicular magnetic anisotropy, interfacial Dzyaloshinskii–Moriya interaction, and efficient spin-orbit torque generation. I illustrate the fulfillment of these requirements through systematic materials and interface engineering and highlight novel device functionalities.

The second section, *Career Development Plans*, details my academic trajectory, ongoing research projects, and future goals. Since completing my

PhD in 2011, which investigated Heusler alloys and dilute magnetic oxides, my research has transitioned from fundamental material characterization towards the development of advanced spintronic heterostructures. In 2015, my first national research grant (SPINCOD https://c4s.utcluj.ro/SPINCOD/spincod.html) explored critical surface and interface phenomena in ultrathin Heusler alloy films for potential applications in spintronic devices. We systematically assessed the prospects of incorporating these materials into emerging spintronic devices, particularly aiming to enhance device stability, reduce power consumption, and enable higher-density data storage

In 2018, I secured a second national grant (SOTMEM https://c4s.utcluj.ro/SOTMEM/sotmem.html), investigating spin-orbit torque-induced magnetization switching in low-resistivity nonmagnetic materials such as platinum (Pt) and palladium (Pd), improving device efficiency and scalability in memory applications.

Furthermore, current-induced manipulation of chiral domain walls and magnetic skyrmions has emerged as a highly promising area within spin-orbitronics, particularly due to their potential in ultra-low-power spin-based logic and memory devices. In the framework of the SPINSYNE project (https://c4s.utcluj.ro/SPINSYNE/spinsyne.html), we were among the first to experimentally demonstrate that spin-orbit torque-driven motion of chiral domain walls and skyrmions in magnetic systems is influenced by chiral damping, impacting their current- and field-driven dynamics. Additionally, we evicenced two novel functionalities in devices exploiting chiral domain walls: diode-like rectification behavior and domain wall routing capabilities. These findings underscore the potential of spin-orbitronics in not only conventional data storage and computation but also in innovative computing paradigms like neuromorphic systems.

Beyond conventional heavy metals, topological insulators (TIs) such as Bi_2Se_3 and Bi_2Te_3 are gaining attention in spin-orbitronics due to their topologically protected surface states with spin-momentum locking, leading to efficient charge-to-spin conversion and reduced spin relaxation. These materials exhibit robust spin coherence and large spin-orbit torques at room temperature, beneficial for energy-efficient manipulation of ferromagnetic layers in TI/FM heterostructures. Integrating TIs with two-dimensional quantum materials enables valleytronics, allowing simultaneous control of spin and valley degrees of freedom, enhancing information density and enabling multi-state logic operations. Other future research plans include integrating solid-state electrolyte layers to electrically modulate spin-orbit coupling, aiming for unprecedented device performance and efficiency. Obtaining habilitation will strengthen my contributions to spin-based technologies, supporting strategic industry-oriented advancements.

Looking forward, spin-orbitronics offers transformative potential for future computing technologies beyond CMOS. It promises low-power, high-speed applications, including spin-orbit torque magnetic random-access memory, scalable logic architectures, and neuromorphic computing, which could significantly advance artificial intelligence and computational efficiency. My laboratory at C4S/TUCN is well-equipped, featuring advanced deposition systems and characterization tools, ideal for training doctoral candidates in materials engineering and spintronic device fabrication. My continued research, leveraging advanced deposition methods and materials engineering, aims to position C4S/TUCN at the forefront of this globally impactful and rapidly evolving research field.