Summary

Spintronics aims to utilize the spin degree of freedom in electrons to develop innovative applications in information storage and computing. Unlike traditional memory devices that rely on magnetic fields and the charge properties of electrons, spintronic devices offer several key advantages, including non-volatility, faster data processing speeds, higher integration densities, and lower power consumption. However, a major challenge in this field is the efficient generation and detection of pure spin currents, which carry information from the injector to the detector through the spin channel. In conventional memory elements, the free ferromagnetic layer is separated from the fixed layer by a non-magnetic spacer, and switching the free layer's state between 0 and 1 is achieved by applying local magnetic fields. This approach, however, is limited in terms of speed, scalability, and energy efficiency due to the requirement of relatively high magnetic fields. Spin currents, in contrast, can switch the magnetization of the free layer by exerting torque without needing magnetic fields, a principle utilized in Spin-Orbit Torque Magnetic Random Access Memory (SOT-MRAM) devices. SOT-MRAM leverages the high spin-orbit coupling (SOC) of materials to switch the magnetic state of a bit cell, offering significant improvements over traditional RAMs. Here, spin currents are generated by the spin Hall effect when a charge current passes through the high SOC layer on which the memory element is placed. This not only eliminates the need for magnetic fields but also reduces the threshold current density and Joule heating across the stack. However, the use of heavy metals like platinum, which are limited in availability and can be economically unviable, has been a constraint. In this context, quantum materials with high SOC and efficient spin propagation have emerged as superior alternatives. These materials, such as transition metal dichalcogenides (TMDs), topological insulators (TIs), and altermagnets (AMs), offer unique electronic and magnetic properties, making them ideal candidates for advanced spintronics. Their introduction is expected to revolutionize memory devices, enabling faster, more energy-efficient operation, and paving the way for smaller,

more powerful technology nodes. Integrating these quantum materials into conventional technologies like Hard Disk Drives (HDDs) could drastically enhance performance, potentially allowing HDDs to compete with or even surpass solid-state drives (SSDs) in speed while maintaining high storage capacities.

In this thesis, we focused on using MoS_2 as a transition metal dichalcogenide (TMD), Bi_2Se_3 as a topological insulator (TI), and RuO_2 as an altermagnet (AM). To evaluate the efficiency of these materials, spin pumping was employed, a versatile technique that has gained significant attention for studying spin dynamics in thin films. This method is particularly valuable due to its simplicity, non-invasive nature, and ability to directly measure spintronic parameters while addressing impedance mismatch issues. TMDs are typically prepared as monolayers or in few-layer forms, often using techniques like mechanical exfoliation or chemical vapor deposition. However, these methods often limit the film's area and can result in discontinuous layers. To overcome this, current research is focusing on expanding the deposition area for more continuous films. In our study, we successfully prepared large-area, continuous thin films of MoS_2 using magnetron sputtering to explore extended functionalities. We performed spin pumping experiments, where spins were pumped from an amorphous low-damping ferromagnet, CoFeB (CFB), into the MoS_2 layer.

Our results revealed a high inverse spin Hall effect (ISHE) voltage signal, with a spin Hall angle comparable to that of platinum. Additionally, we measured a long spin diffusion length of 7.83 nm. Notably, MoS_2 not only facilitated efficient spin pumping but also induced anisotropy in the otherwise isotropic ferromagnetic (FM) CoFeB layer. Initially, CoFeB exhibited isotropic behavior, but the presence of the MoS_2 underlayer introduced a distinct anisotropy. This change is possibly due to orbital hybridization between the Mo atoms in MoS_2 and the Co and Fe atoms in CoFeB at the interface, which may allow the magnetization to preferentially align within the plane of the film. Low SOC materials such as Cu, Ag, Au, and Ti have been used as spacer layers between quantum materials and ferromagnets to enhance overall spin-to-charge conversion efficiency. In

our study, we introduced a copper (Cu) spacer layer, known for its long spin diffusion length, between MoS_2 and the ferromagnet. This significantly improved the spin Hall angle of MoS_2 by an order of magnitude, increasing it from 0.02 to 0.30. Additionally, we fabricated heterostructures consisting of Bi_2Se_3 films, deposited via electron beam evaporation, with Co_2FeAl (CFA) spin sources grown by magnetron sputtering. Here, CFA is a Heusler alloy which exhibits high spin polarization. The Bi_2Se_3/Co_2FeAl films demonstrated efficient spin pumping, with a spin diffusion length of 5.6 nm and a spin Hall angle of 0.048. The strong spin polarization of the Bi_2Se_3 surface states probably induce additional anisotropy in CFA, altering its energy landscape and making specific magnetization directions more favorable. Notably, a 4nm Bi_2Se_3 underlayer increased the anisotropy of CFA; however, as the thickness of Bi_2Se_3 increased, the anisotropy decreased, eventually falling below that of the bare CFA layer. This behavior has been reported to be attributable to surface state coupling between the top and bottom layers of Bi_2Se_3 at 4nm. With increasing Bi_2Se_3 thickness, this coupling weakens, allowing bulk effects to dominate over surface states, thereby reducing interaction with CFA. Following a similar approach, we inserted a Cu layer between Bi_2Se_3 and CFA to further enhance the spin-to-charge conversion efficiency. The presence of the Cu layer resulted in a 1.7-fold increase in the spin pumping voltage and the spin Hall angle. Finally, we successfully grew RuO_2, an altermagnetic material, with a (110)-oriented crystal structure on an MgO substrate. Our findings revealed a small spin memory loss (15%) and high interfacial spin transparency (90%) in the RuO_2/MgO system. These results highlight the potential of these materials for advanced spintronic applications, demonstrating their effectiveness in spin dynamics and spin-to-charge conversion.