Growth and Investigation of Ferromagnetic and Antiferromagnetic Quantum Materials for Spintronic Devices

Topological quantum materials are extremely promising for next-generation of spintronic devices such as magnetic memories due to their non-trivial band topology. Recently, kagome ferromagnet (FM) Fe_3Sn_2 and antiferromagnet (AFM) FeSn, which belong to the Fe_nSn_m-family (m: n = 1:1, 3:2, 5:3) have emerged as promising magnetic quantum materials due to their intriguing topological properties, such as the presence of Dirac nodes, Weyl points, flat bands, and topological surface states in their band structure. To date, most of the experimental and theoretical studies on Fe_3Sn_2 and FeSn have been predominantly concentrated on bulk single crystals. However, the experimental realization of the thin film of these materials with stable phase and stoichiometry is challenging. Thin films of these materials and their heterostructures are desirable for spintronics-based device applications. The topological and quantum properties can be further tuned in thin films through reduced dimensionality. In addition, thin films allow the creation of heterostructures with other materials, which may host emergent phenomena. This motivated us to investigate the growth of thin films of Fe_3Sn_2 and FeSn and their heterostructures for spintronics applications. In this thesis, we establish the growth of thin films of ferromagnetic Fe_3Sn_2 and antiferromagnetic FeSn and NiO thin films. Subsequently, we grow heterostructures of these materials with either heavy metal or ferromagnet (in the case of FeSn and NiO) to study spin pumping behaviour, which is technologically important for next-generation magnetic recording devices.

In the case of Fe_3Sn_2, we first demonstrate the growth of polycrystalline ferromagnetic Fe_3Sn_2 thin films on Si/SiO_2 substrates by using a Pt seed layer. Our structural and magnetic measurements indicate that a pure ferromagnetic phase of Fe_3Sn_2 thin films with higher saturation magnetization of $M_S = 464 - 640$ emu/cc is formed for the Pt seed layer, while a mixed-phase (consisting of ferromagnetic Fe_3Sn_2 and antiferromagnetic FeSn) with a lower M_S is formed for the Ta seed layer. The anomalous Hall effect measurements were performed to determine the role of the electronic bands due to the kagome structure of Fe_3Sn_2. We found a non-zero intrinsic anomalous Hall conductivity (σ_{xy}^{int}), a large value anomalous Hall coefficient (R_S), and an anomalous Hall angle (θ_{AHA}) indicating the intrinsic origin of anomalous Hall resistivity in Fe_3Sn_2 thin films. The ferromagnetic resonance study performed in Pt/ Fe_3Sn_2 based heterostructure allows us to determine the intrinsic damping of Fe_3Sn_2 to be $\alpha_{int.} = (3.8 \pm 0.2)\times10^{-2}$. Furthermore, the effective spin mixing conductance of Pt/ Fe_3Sn_2 is found to be $g_{eff}^{\uparrow\downarrow} = (11.7 \pm 0.6)$ nm^{-2}, which is comparable to other ferromagnet/heavy metal systems.

In the case of FeSn, we demonstrate epitaxial growth using the Pt seed layer on the sapphire vii substrate. The antiferromagnetic phase was confirmed using magnetization measurements as well as the presence of exchange bias in $FeSn/Ni_{80}Fe_{20}$ bilayers. A large spin mixing conductance of $g_{eff}^{\uparrow\downarrow}$ = (117

± 0.6) nm^{-2} is found in FeSn/Py which is nearly two-order of magnitude higher compared to the standard ferromagnet/heavy metal systems. The large value of $g_{eff}^{\uparrow\downarrow}$ is promising for application and indicates the possible role of the kagome lattice of FeSn. We have also investigated the spin pumping in the antiferromagnet NiO/Py system and we showed that the $g_{eff}^{\uparrow\downarrow}$ of an optimized polycrystalline-NiO/Py system can reach the value that for an epitaxial-NiO/Py system.

In the final part of the thesis, we numerically explore the potential application of magnetic quantum material-based heterostructures. Magnetic skyrmions are highly promising for the next generation of racetrack memory devices as they offer ultra-dense storage capacity and low power consumption in comparison to domain-wall-based racetrack memory devices. In this thesis, we numerically studied the nucleation process of the FM and AFM skyrmions in racetrack devices. We found an ultrafast nucleation single/multiple AFM skyrmion using in-plane spin-polarized current in an AFM material. In addition, our method also shows low energy consumption for nucleation using in-plane spin-polarized current compared to out-of-plane spin-polarized current. We stabilize FM skyrmion for a range of external magnetic fields in ferromagnet Fe_3Sn_2 without using Dzyaloshinskii–Moriya interaction. The strong uniaxial magnetic anisotropy and dipole-dipole interaction of the kagome lattice in Fe_3Sn_2 facilitate the nucleation of both skyrmions and anti-skyrmions.