ABSTRACT

Magnetic systems with Dzyaloshinskii-Moriya interaction (DMI) have attracted significant interest for both technological applications and fundamental physics. The competition of DMI with other interactions such as exchange interaction, perpendicular magnetic anisotropy (PMA), dipolar interaction, and Zeeman energy stabilizes a variety of nontrivial and nanoscale magnetic spin textures. These interactions can be tuned through material parameters, layer thickness, and geometrical confinement. DMI has been predicted in several systems, including B20 crystals, ultrathin ferromagnets, and heavy-metal/ferromagnet (HM/FM) heterostructures. In bulk non-centrosymmetric ferromagnets such as MnSi and FeGe, DMI arises intrinsically from broken inversion symmetry and strong spin-orbit coupling (SOC), with the DMI vector aligned along the line connecting neighboring spins. In contrast, ultrathin FM/HM (example: Ir/Fe/Co/Pt, Ir/Co/Pt, Co/Pt/Al, FePd/Ir etc.) multilayers system exhibit interfacial DMI (i-DMI), originating from SOC and structural inversion asymmetry at the interface. The DMI Hamiltonian between two neighbors spins $\boldsymbol{S_i}$ and $\boldsymbol{S_j}$ is given by $\boldsymbol{H_{\mathrm{DMI}}} = \mathbf{D}_{\boldsymbol{ij}} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$, where $\mathbf{D}_{ij}$ determines the nature and stability of chiral spin textures. In heterostructures, $\mathbf{D}_{ij}$ is perpendicular to the spins joining line direction, favoring Néel-type spin configurations, whereas in bulk systems it is parallel, stabilizing Bloch-type textures. Ultrathin FM/HM systems support chiral spin textures over a wide temperature range, including room temperature, and at low magnetic fields, making them promising for energy-efficient spintronic applications.

The main objective of this thesis is to investigate the micromagnetic behavior, magneto-transport, and charge-carrier dynamics in FM/HM multilayers with interfacial DMI. As an initial step, we study the competition between dipolar interactions and i-DMI by using the micromagnetic simulation. The dipolar interaction is tuned by varying the size of confined Co/Pt (FM/HM) nanodiscs. In such systems, changing the nanodisc diameter modifies the magnetic volume and stray-field distribution, thereby controlling the balance between long-range magnetostatic energy and short-range exchange and DMI interactions. While i-DMI favors Néel-type spin rotation, dipolar interactions favor Bloch-type configurations. As a result, we observe a stable novel spin texture, which we named the 'X'-state, along with other $k\pi$-skyrmion states during magnetic field sweeps. This novel state is characterized by two domains of the same polarity connected by hybrid domain walls. We also systematically achieve this 'X'-state at different DMI and PMA values. This study suggests the important role of dipolar interactions in confined nanostructures.

Out of these textures, skyrmions stand out due to their strong potential for spintronic applications. Secondly, we investigate the thermal-gradient-driven skyrmion dynamics, which offers a promising route toward green spintronics by enabling the use of waste heat for information transport, storage, and processing. Micromagnetic studies in this part show that a thermal gradient generates stochastic torques, driving Néel skyrmions toward the hotter region in Co/Pt nanoracetracks. We optimized the racetrack's geometric and magnetic material parameters to achieve a skyrmion trajectory with a near-zero skyrmion Hall angle, which remains nearly zero within a certain of material parameters and the dimensions. Our thermal-gradient-induced skyrmion dynamics with a near-zero skyrmion Hall angle demonstrate the efficiency of using waste heat. Furthermore, it was found that the combined electrical spin-transfer torque and Joule-heating-induced thermal gradients give rise to distinct dynamical regimes, each governed by the dominant driving mechanism.

The next aspect of this thesis focuses on the experimental investigation of magneto-transport behavior in FM/HM multilayer systems with i-DMI. We consider two systems: synthetic antiferromagnetic (SAF) multilayers of Pt/Co/Ru/Pt/Co and Pt/CoFeB/AlO$_x$ multilayers. In SAF systems, the ferromagnetic Co layers act as reference layers for each other. Due to the larger thickness of the bottom Pt layer, a significant spin current is generated, causing the magnetotransport signal from the bottom layer to dominate the overall measurement. Our results provide strong evidence of spin-current contributions to both Hall and magnetoresistance (MR) signals in FM/HM multilayers. This spin current also contributes to an additional Hall signal beyond conventional mechanisms. These findings provide a useful framework for understanding and diagnosing magnetotransport behavior in FM/HM systems.

Additionally to understand magnetotransport behavior in the presence of various chiral spin textures-such as isolated skyrmions, skyrmion lattices, labyrinthine domain walls, and mixed skyrmion-labyrinthine states, we investigate skyrmion-hosting Pt/CoFeB/AlO$_x$ multilayers. We show that the observed extra Hall resistivity, often attributed solely to the topological Hall effect, arises from a combination of genuine topological contributions and additional mechanisms can be linked to chiral domain walls, spin-current contribution and worm-like textures in this system. Our results provide a consistent explanation for discrepancies between electrically measured and microscopy-based estimates of skyrmion density. Our magnetotransport results of both samples highlight the pivotal role of spin-current and other mechanism in both Hall and magnetoresistance (MR) measurements.

Finally, we investigate low frequency charge-carrier dynamics using $1/f$ noise spectroscopy in both skyrmion-hosting FM/HM multilayer and SAF systems. The $1/f$ noise measurement is a sensitive technique for probing indirectly low-frequency charge-carrier dynamics and capturing charge trapping-detrapping processes, as well as microscopic fluctuations in electronic and magnetic systems. We observe that the noise power spectral density (PSD) exhibits pronounced peak-like features as a function of external magnetic field. In Pt/CoFeB/AlO_x multilayers, the results demonstrate a strong correlation between PSD and skyrmion nucleation and evolution. These features in the PSD are enhanced in the stabilization regions of different chiral spin textures. Notably, the charge-carrier dynamics become slightly faster prior to skyrmion formation. However, the low-frequency charge-carrier dynamics become slower when the skyrmion lattice stabilizes. In this region, the PSD becomes significantly higher, indicating an enhancement in conductance fluctuations. In SAF systems, the PSD increases during Co layer switching and with variations in magnetic susceptibility (χ). In the antiferromagnetic coupling region, the PSD is significantly enhanced as χ varies.