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論　文　内　容　の　要　旨

The information storage and processing are fundamental and essential to all information and communications technologies, which are also indispensable to our fast-paced information-driven modern society. The revolution of information storage and processing is usually associated with the discovery and development of new information carriers and media. Recently, skyrmions in magnetic materials with chiral or competing exchange interactions are found to be promising building blocks for next-generation information storage and processing applications, such as advanced magnetic memories and novel spintronic computing devices. The magnetic skyrmions are quasiparticle-like nanoscale magnetic spin configurations, which have several promising properties including the topologically non-trivial structure, unique topology-dependent dynamics, reasonably good stability and mobility, and low energy consumption. The understanding of dynamic behaviors of magnetic skyrmions is important and necessary for developing practical information-related applications based on magnetic skyrmions.

In this dissertation, we theoretically and numerically study the dynamics of magnetic skyrmions in confined nanostructures driven by spin-polarized currents or spin waves, as well as the possible advanced applications based on the manipulation of magnetic skyrmions, mainly in the framework of micromagnetics. The dissertation can be divided into three major parts as described below.

In the first part, we focus on the motion dynamics of an isolated magnetic skyrmion driven by spin-polarized currents in both thin films, monolayer and multilayer nanotracks. Both the Slonczewski-like and Zhang-Li spin-transfer torques are considered as the driving forces. We study the magnetic skyrmion-hosting material systems with either chiral exchange interactions or frustrated exchange interactions. The chiral exchange interactions considered are the interface-induced Dzyaloshinskii-Moriya interactions. The frustrated exchange interactions considered are the ferromagnetic nearest and antiferromagnetic next-nearest Heisenberg exchange interactions. This work shows that the current-induced dynamics of an isolated magnetic skyrmion depends on both the geometric and material properties of skyrmion-hosting nanostructures. We also show that the Slonczewski-like spin-transfer torques are more efficient than the Zhang-Li spin transfer torques for driving the skyrmion motion.

Besides, we reveal that the magnetic skyrmions driven by spin-polarized currents in conventional ferromagnetic materials may show the skyrmion Hall effect due to their special topological structures, namely, the magnetic skyrmions move at an angle with respect to the driving force direction. We demonstrate that the skyrmion Hall effect can either be controlled by locally modifying the magnetic parameters or totally eliminated by fabricating the synthetic antiferromagnetic nanotracks. Especially, the perfect elimination of the skyrmion Hall effect is found to be beneficial for the high-speed transport of information-carrying magnetic skyrmions in narrow channels. Moreover, we reveal that the magnetic skyrmions driven by spin-polarized currents in frustrated ferromagnetic films show novel dynamic behaviors, which can drastically change from the translational motion to the circular motion by triggering the helicity locking-unlocking transition. Namely, the skyrmion helicity is found to be coupled to the center-of-mass skyrmion dynamics, which is a unique property for the magnetic skyrmions in the frustrated magnetic system.

In the second part, we focus on the motion dynamics of an isolated magnetic skyrmion driven by spin waves in both thin films and confined nanostructures with different damping coefficients, where the excited spin waves are propagating either in the longitudinal or transverse direction.

This work demonstrates the feasibility and method to drive magnetic skyrmions in complex nanostructures, such as L-corners, T-junctions, and Y-junctions, which are important components for building future spintronic circuits. By investigating the skyrmion velocity versus driving force relation in nanotracks, we reveal that there are different scenarios of the skyrmion dynamics driven by transverse spin waves. At low driving force, the magnetic skyrmion smoothly moves along the nanotrack and does not suffer any significant deformations. At large driving force, the internal modes of the magnetic skyrmion can be excited, resulting in the emission of spin waves by the magnetic skyrmion itself. The magnetic skyrmion may also be destroyed at large driving force. We also reveal that the transverse driving scheme is more efficient than the longitudinal driving scheme for controlling and delivering magnetic skyrmions in narrow channels due to the damping of spin waves. We further show that motion direction of an isolated magnetic skyrmion in complex nanostructures can be controlled by multiple spin wave sources placed at different positions.

In the third part, we numerically demonstrate that the magnetic skyrmions can be used as the information carriers in a number of advanced spintronic applications, which include the racetrack-type memories, logic computing gates, and transistor-like functional devices. We first point out possible skyrmion candidates for carrying information in different magnetic material systems. We show that the merging of two isolated magnetic skyrmions as well as the duplication of an isolated magnetic skyrmion can be flexibly realized by utilizing the current-driven skyrmion-domain wall conversion mechanism in a Y-junction. We demonstrate that basic binary logic computing operations can be implemented based on the merging and duplication of magnetic skyrmions. In addition, we show that the transport of magnetic skyrmions in narrow channels can be controlled by voltage gates, which can be used for building transistor-like functional devices. This work not only provides guidelines for designing novel electronic and spintronic devices based on magnetic skyrmions, but also highlights the importance of magnetic skyrmions in practical and industrial applications.

Finally, at the end of the dissertation, we point out future research directions on magnetic skyrmions in terms of skyrmion-hosting materials, skyrmion structures, and skyrmion driving forces. We suggest the exploration of magnetic skyrmions and antiskyrmions in antiferromagnetic and ferrimagnetic materials driven by spin-polarized currents, spin waves, and electric fields.