論文題目
Study on Dynamics of Topological Textures in Magnets
（磁性体中におけるトポロジカルテクスチャのダイナミクスの研究）

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Manipulation of spin textures has been attracting great interests over decades. The field-driven motion of magnetic domain walls and bubbles had intensively studied during the 1970s aiming at bubble memories. Actually, bubble memories were commercialized around 1980. However, the field-driven motion of domain walls faced a crucial difficulty that a large magnetic field is required to overcome the pinning, which impedes their motion. A new mechanism to drive the motion of spin textures, so-called spin transfer torque, has been introduced in 1996. This is the transfer of spin angular momenta from the flow of spin-polarized electrons to localized spins constituting spin textures, and is shown to be effective for manipulating domain walls and bubbles compared with a magnetic field. Although there already exists a prototype of the racetrack memory where information is stored in an array of domain walls manipulated by an electric current, a threshold current density to induce their motion is still large. Therefore, many researchers all over the world are struggling to reduce the threshold current density. In this direction, magnetic skyrmion, a swirling spin texture with nontrivial topology, is a particularly interesting object. Soon after its recent discovery in chiral-lattice magnets, the current-induced motion has been investigated. Surprisingly, it was reported that the threshold current density to drive the motion of skyrmions is about five orders of magnitudes smaller than that of domain walls, which triggered more intensive researches on skyrmions from both theoretical and experimental sides.

In this thesis, we study theoretically the manipulation of spin textures, focusing mainly on magnetic skyrmion. We perform a large-scale micromagnetic simulation based on the Landau-Lifshitz-Gilbert equation. Combining the obtained numerical data with analytic methods, we extract the physical pictures of skyrmion dynamics, which is often compared to the dynamics of magnetic domain walls. The major conclusions are as follows.

First, we provide a theoretical description of the experimental fact that the threshold current density for skyrmions is much smaller than that of domain walls. Comparing two phases in a chiral magnet, the helical (a periodic array of the domain walls) and the skyrmion crystal phases, we found two mechanisms for skyrmions to reduce the threshold current density. One is the Magnus force acting on the skyrmion, which is proportional to the skyrmion number and absent for the helical phase. The other is the deformation of skyrmions themselves and the lattice of magnetic skyrmions, which results in the reduced pinning force for the skyrmion crystal phase. As a result, the relation between a velocity and a driving current density for the skyrmion motion becomes universal, that is, independent of the Gilbert damping constant α and the nonadiabaticity β, and insensitive to impurities.

The research above is for skyrmions in a free space where boundary effects can be neglected. The next important step is to investigate the current-induced motion in constricted geometries toward "skyrmionics". Here, the skyrmion is subjected to a repulsive potential from the boundary in the presence of the Dzyaloshinskii-Moriya interaction, and the repulsive potential dramatically changes the skyrmion dynamics. In a natural setup where the current is flowing in the direction parallel to the circuit-shaped sample, the velocity-current relation becomes the same as that of the domain wall, i.e., the velocity is proportional to β/α without the pinning and the threshold current density is large with the pinning. At this stage, one may think the advantage of skyrmion is lost in a narrow region. However, in the setup where the current is in the direction perpendicular to it, the velocity is much enhanced by a factor of $1/\alpha$ with the maximum value determined only by the strength of the repulsive potential from the edge. In addition, the insensitivity to the impurities in an infinite plane without boundary holds true in this case. Therefore, the latter setup is ideal for skyrmion devices, in which a high-speed manipulation and a low energy-consumption are required.

Above studies focused mainly on the case of time-independent driving force at zero-temperature. When we are interested in the time-dependent one, a mass enters into the dynamics as an important quantity. We found that the current-driven skyrmion dynamics shows almost no inertial effect, whereas the field-driven dynamics is explained by a large effective mass in a generalized Thiele equation. Another phenomenon in which a mass plays a crucial role is thermal diffusion. The thermal diffusion of a skyrmion is also described by a large effective mass. Moreover, diffusion is suppressed by the cyclotron motion and is proportional to α. These findings mean that the thermal fluctuation does not have a large influence on the position of a skyrmion, and at the same time, a skyrmion responds quickly to time-dependent current. These features demonstrate the advantage of skyrmions as information careers.

We can consider many ways to manipulate spin textures other than an electric current. Recently, magnon-induced motion has been reported, where magnons are excited and propagate by a temperature gradient. To clarify the elementary process involving a single skyrmion and magnons, we study the scattering between a skyrmion and magnons. We first confirm the stability of a skyrmion. Although the skyrmion and the magnons are made of the same spins, the identity of the skyrmion is intact in the scattering process. Second, the incident magnons are scattered by a large angle by an emergent magnetic field produced by the skyrmion. In turn, the skyrmion is pulled out to the direction opposite to the incoming wave. A non-Newtonian momentum associated to the skyrmion enables one to describe this peculiar scattering by momentum exchange.

Now that a lot of knowledge on skyrmion dynamics is accumulated, it is time to design skyrmion-based devices. The external stimuli, such as local heating, magnetic field, electric field and electric current, can trigger the creation and annihilation of skyrmions. These procedures can be achieved within nano or pico seconds. Using these elementary functions of skyrmions, we propose some models of memory devices.

Two collaborative works with experimentalists are also included in the thesis. One is on the strain control of the skyrmion. It has been observed that anisotropic tensile strain to the sample produces a large anisotropic deformation of the crystallized form of skyrmions. The experimental results are compared with the simulation, and we conclude that the anisotropic strain as small as 0.3% corresponds to the change in the anisotropy of the Dzyaloshinskii-Moriya interaction as large as 20%. The other is on the suppression of the Bragg peaks of skyrmion crystal under a current. Without current, three Bragg peaks are equivalent because of the symmetry. However, the current breaks the degeneracy completely, i.e. all the three peaks become inequivalent. This theoretical prediction stimulated the corresponding neutron scattering experiment, and the experiment is now ongoing.

Final part of the thesis is on the current-induced dynamics of the magnetic domain wall with many Bloch lines. In the researches on the skyrmion dynamics, we have recognized the importance of the skyrmion number, or the solid angle, which results in a small threshold current density. The same idea can be applied to the domain wall. When one introduces a Bloch line, the wall gets nonzero skyrmion charge distribution around the Bloch line. Then one expects that a threshold current density will be much smaller than that of the domain wall without any internal structure. To analyze the dynamics, we derived the equation of motion in terms of the wall-normal displacement and the wall-magnetization orientation. We solved it to show that the velocity became similar to that of a skyrmion. More importantly, the threshold current density is even smaller than that of a skyrmion by a factor of α. This is in sharp contrast to the magnetic-field-driven case, where the mobility is suppressed by the existence of Bloch lines.

In conclusion, we have investigated the dynamical properties of spin textures with various driving methods such as an electric current, a magnon, a heating, a magnetic field, and an electric field. The

importance of the solid angle subtended by spins is highlighted in the study on skyrmions as well as that on domain walls with Bloch lines. These studies will pave a way for the spin-texture-based devices in the next generation.