Current-Driven Dynamics of Magnetic Domain Wall in Ultrathin Metallic Structures

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論 文 内 容 要 旨

Magnetic domain-wall (DW) motion in ultrathin film magnetic structures have gained attention for their prospective application for spintronic devices. A DW in a ferromagnet represents the transition region between two magnetic domains with different magnetization directions. The motion of DW in out-of-plane magnetized thin films can be controlled by magnetic field and current and serves as promising candidates for low-power spintronic devices. With the possibility of realization of these new generation spintronic devices, understanding of the factors which determine the stability, data retention and the performance of DW motion needs to be addressed. Current offers a more practical route for the manipulation of DW rather than magnetic field for their use as memory elements due to the scalability. Thus, it is important to quantify the interaction of DW with current which are more commonly referred to as *spin-transfer torques*. Interestingly, both the DW configuration and interaction of DW with current in out-of-plane magnetized systems depends on the existence of additional interactions arising from spin-orbit interaction and symmetry breaking at interfaces. This interaction referred to as *Dzyaloshinskii-Moriya interaction* enables efficient DW motion in out-of-plane magnetized systems with a velocity much larger than the case where the spin-transfer torque adiabatically drives the DW. Thus, investigation of DW configuration and the nature of interaction of current with DW are crucial issues which should be addressed for the successful implementation of DW-motion memory devices and also from the viewpoint of fundamental understanding.

In **chapter 1**, the basic outline for the background and motivation of the proposed investigation on DW-motion properties of polycrystalline metallic thin films is provided.

In **chapter 2**, the basic physics governing the dynamics of DW motion are described. The application of forces to a magnetic DW results in several dynamical behaviors depending on the magnitude and nature of the force. For small applied forces, an interesting regime of DW motion is observed which is called *creep* regime. The velocity-force characteristics in the *creep* regime follows a power-law scaling relation and enables a unique way for the understanding of several interactions which govern magnetic DW dynamics in out-of-plane magnetized systems. In this thesis, DW *creep* motion has been utilized for two purposes: *understanding of the nature of interaction of DW with magnetic field and current in out-of-plane magnetized systems and investigation of the DW configuration under strong spin-orbit interactions*. The first part deals with the interaction of DW with magnetic field and current which has been a longstanding issue in the context of magnetic metallic systems. The basics of the nature of interaction and the previous experimental and theoretical investigations has been summarized. This part concludes with the identification of the open questions requiring further investigations which has been studied in detail in the successive chapters. Recent investigations have revealed that in systems with strong *spin-orbit interactions*, DW dynamics and in particular DW configuration could be entirely different as compared to the conventional Bloch DW configuration. This interaction, called *Dzyaloshinskii-Moriya interaction (DMI)*, favors orthogonal alignment of neighboring spins, causing stable Néel domain walls of well-defined chirality. In the second part of this chapter, we review the basics of DMI and discuss the relevance of DW *creep* motion for the quantification of the DMI in out-of-plane systems with strong spin-orbit interactions. This section is concluded with the open questions which needs further investigations. Finally, this chapter is concluded with the measurement techniques used for the experimental work in this thesis.

In **chapter 3**, the slow motion of DW under the action of two different driving forces; magnetic field and/or electric current, has been investigated. This regime is the well-known *creep* regime and is a general phenomenon observed in nature. DW velocity in this regime obeys a scaling relation with respect to driving forces manifesting into universality classes representing the core dynamics of motion. It is shown for the first time that in a metallic system *Ta/CoFeB/MgO*, the universality classes for DW motion driven by magnetic field and current are different. This indicates that the nature of interaction of DW with magnetic field and current are different in metallic system. It turns out that this difference originates from the different nature of the torque acting on the DW, and for the case of current-driven *creep* the universality class is determined irrespective of the intricacies of material disorder unlike the case for field-driven *creep*. Further investigations reveal that the major driving force for current-induced DW *creep* can be attributed to the adiabatic spin-transfer torque and thus the obtained universality class has been identified as the universality class for adiabatic spin-transfer torque.

In **chapter 4**, the static configuration of DW under Dzyaloshinskii-Moriya interaction (DMI) in out-of-plane magnetized systems has been investigated. It has been established that for sufficiently large DMI, the Bloch configuration of DW can be completely transformed into Néel configuration due to the longitudinal effective field from DMI acting on DW. The configuration of DW has severe effects on the current-driven dynamics of DW and forms an important regime of study. Both the slow motion of DW or *creep* motion and the fast motion of DW or *flow* motion can be used as a tool for the quantification of DMI. While for some cases, the evaluation of DMI from these two regimes agree, other investigation show marked differences indicating the requirement of the investigation of the underlying mechanism. For the investigation of this discrepancy, I compare the experimental results from two different material systems: *W/CoFeB/MgO and Pt/[Co/Ni]* which provides a unique situation due to the difference in the nature of the pinning strengths experienced by DW. I show that the quantification of DMI from the *creep* motion of DW, which requires much less time and careful setup, provides reliable information only when pinning strength is small. On the other hand, the fast-motion technique is insensitive to such requirement and can be utilized for wider variety of cases irrespective of the details of the sample.

In **chapter 5**, the summary and conclusions obtained from my study are provided.

To summarize, this work clarifies the versatile ability of the DW *creep* as a tool to study the nature of DW configuration and its interaction with the applied external forces (magnetic field, current). Since the *creep* motion obeys a universal law, the established technique can be easily extended from one material system to another. The characterization of the nature of DW and the interaction of DW with various driving forces are important issues for DW motion, and *creep* motion offers a stable and robust technique for settling these issues. Thus, the obtained insight is expected to promote the understanding of the physics of DW and its device applications.

論文審査結果の要旨

強磁性体における磁壁の運動は、スピントロニクス素子の特性を決める一つの大きな要因となる。特に熱活性下で磁場や電流などの駆動力によって生じる磁壁のクリープ運動は、高温超伝導体中の磁束や地底プレートの運動などに共通する物理を有することから、スピントロニクスはもとより、固体物理学や統計力学などの分野からも注目されている。本論文は、強磁性金属薄膜における磁壁のクリープ運動に関し、磁場や電流によって生ずる磁壁のクリープにおいて成り立つスケーリング則において指数μで特徴づけられる普遍性クラスを決める因子、および磁壁のクリープ運動と強磁性/非磁性界面において発現される反対称な交換相互作用（ジャロシンスキー・守谷相互作用：DMI）との関係を明らかにした結果をまとめたものであり、全編5章からなる。

第1章は序論である。

第2章では、本研究で扱われている現象や測定方法に関するこれまでの知見をまとめている。

第3章では、Ta/CoFeB/MgO強磁性金属薄膜における磁壁のクリープ運動に関する実験結果が示され、普遍性クラスが決まるメカニズムが議論されている。磁気光学的手法を用いたイメージングにより、磁場印加時、電流印加時における磁壁のクリープ運動とその温度依存性を明らかにし、クリープ運動の普遍性クラスが両者で異なる（磁場：$\mu = 0.23\pm0.07$, 電流：$\mu = 0.39\pm0.06$）ことを強磁性金属で初めて見出した。さらに今回用いた強磁性金属では磁場印加時に働くトルクと直交するトルクが電流印加時に働くことを明らかにし、これが異なる普遍性クラスが観測された理由であることを見出している。すなわち、電流による磁壁のクリープでは、材料自体は本質ではなく、磁壁に働くトルクの対称性が普遍性クラスを決定することを明らかにした。従来の研究では、強磁性半導体と強磁性金属で異なる実験結果が報告されており、統一的な理解が待たれていた。本成果はこれに応えるものであり、強磁性体における磁壁のクリープ運動の基礎的理解を確立したものであって、学術的に高く評価できる。

第4章では、垂直磁化容易軸を有する磁性金属膜であるW/CoFeB/MgO積層膜、及びPt/[Co/Ni]積層膜を取り上げ、垂直磁場と面内磁場を印加した際に磁壁がゆっくりと運動することで生じる磁区の非対称な拡大の観察から、非磁性/強磁性界面で働くDMIの方向と大きさを求める研究成果が述べられている。まずW/CoFeB/MgO膜では、磁壁の運動が普遍性クラスを示すクリープ運動であること、この場合にはDMI定数Dを決められる（$D = 0.018$ mJ/m^2）ことを明らかにした。一方、Pt/[Co/Ni]膜の磁壁運動は、クリープ運動に合致せず、この測定からDMI定数を決めることはできないことが示されており、磁壁のゆっくりとした運動を用いてDMIを定量的に評価するには、磁壁がクリープ運動することが必要条件であることを明らかにした。これは強磁性積層膜の応用にあたり極めて重要な知見である。

第5章は結論である。

以上要するに本論文は、磁壁のクリープ運動における物理的機構に関し、統一的な理解を提示し、その工学的な利用価値を明らかにしたものであり、スピントロニクスおよび電子工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。