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Research Institute of Electrical Communication, Tohoku University
Center for Spintronics Integrated Systems, Tohoku University
Center for Innovative Integrated Electronic Systems, Tohoku University
WPI-Advanced Institute for Materials Research, Tohoku University

Tohoku University reveals the physics for the mechanism of slow change in microscopic magnetic structures

- Shedding light on a statistical physics of creep motion of elastic interfaces and development of high-performance magnetic memory devices -

<Abstract>

The research group of Professor Hideo Ohno (Research Institute of Electrical Communication, Center for Spintronics Integrated Systems (CSIS), Center for Innovative Integrated Electronic Systems (CIES), WPI-Advanced Institute for Materials Research of Tohoku University) and Associate Professor Shunsuke Fukami (CSIS, CIES) studied in detail a slow change of microscopic magnetic structures in metallic wires induced by external driving forces, commonly called as "creep" motion, and clarified the physics regarding how the driving forces, magnetic field or electric current, acts on the magnetic structure. Previous studies reported that the actions of magnetic field and current are fundamentally different for a semiconductor material, whereas they are the same for a metallic material. The present study revealed that in case when the sample satisfies a certain condition, the current acts on the magnetic structure in a different manner from the magnetic field case, irrespective of the intricacies of material. While a development of high-performance magnetic memory device where the magnetic structure is manipulated by current has been intensively pursued recently, the present findings are expected to facilitate the fundamental understanding to achieve the practical application. This work will be published in online version of *Nature Physics* on December 15 (JST).

<Background and challenges>

All around us, there are many phenomena in which an interface representing a boundary between two configurations/domains gradually moves in one direction under the application of a driving force. Such motion of the interface commonly called as "creep" motion can be observed in a variety of physical systems ranging from fluid wetting/propagation, growth of bacterial colonies, plastic deformation of metallic and polymer molecule materials, motion of earth's plate, and so on. These different physical systems can be described by a scaling law where the interface motion can be expressed as a power of the driving force. The number of power is referred to as a scaling exponent and this is determined from the competition of several microscopic interactions. Interestingly, different diverse physical systems often show same value of the scaling exponent indicating the *universality* of the microscopic phenomena. In other words, systems showing the same value of the scaling exponent belong to the same *universality class*. Research on the universality class of the "creep" motion of the interface is thus an interesting problem in the statistical physics because the macroscopically observed results enable the understanding of the microscopic interactions.

Magnets are composed of many magnetic domains in which the direction of magnetization, North Pole / South Pole, is aligned, and in between, a magnetic domain wall, in which the magnetization direction is gradually changed in nanometer scales, is formed. It has been known that the domain wall can be moved by magnetic field or electric current, and high-performance magnetic memory devices utilizing the domain wall motion have been extensively developed. Also, recent studies revealed that the domain wall show a "creep" motion described by the scaling law when a weak magnetic field or current is applied; however, there has no consensus on its *universality class*. In particular, previous experimental results showed that the universality classes for the field- and current-induced creeps are different for a magnetic semiconductor, whereas those are the same for a magnetic metal.

<Experimental method and results>

The group of Tohoku University studied the universality class of the domain wall creep driven by magnetic field or electric current using a ferromagnetic metal CoFeB (Fig. 1). The stack structure is from the substrate side, Ta (0.5 nm)/ CoFeB(1.2 nm)/ MgO(1.5 nm)/ Ta(1 nm), where the magnetization is designed to point to the out of plane direction due to a specific electronic structure formed at the CoFeB/MgO interface. They fabricated a micrometer-sized wire device through lithography and observed domain wall motion induced by magnetic field or electric current using a microscope with a magneto-optic effect[*1].

They evaluated the domain wall velocity for various magnitudes of magnetic field or electric current while keeping the device temperature constant, from which they derived the scaling exponent. The results indicated that the scaling exponent does not depend on factors such as temperature and wire width, for both magnetic field and current cases, confirming the universality of the observed feature (Fig. 3). Interestingly, unlike the previous study on metallic systems, they found different universality classes between magnetic field and current driven domain wall creeps in the present metallic sample. This means that the actions of magnetic field and current on the domain wall are fundamentally different from each other. The field-driven “creep” was found to belong to a previously known universality class, whereas the current-driven “creep” was found to belong to a different universality class which cannot be explained by the present theories and the scaling exponent was similar to the one observed in the magnetic semiconductor previously. From detailed investigation on the behavior of the domain wall under the application of current, they found that the current gives rise to an adiabatic spin-transfer torque[*2] acting on the domain wall which has a different symmetry to the torque induced by magnetic field. In other words, it was clarified that, for sample in which stack structure is designed so that the adiabatic spin-transfer torque dominantly affects the domain wall, universal creep characteristics appear irrespective of the nature of material, such as metal or semiconductor, the details of microscopic structure.

<Significance of the results>

The present findings possess twofold significance from the viewpoints of fundamental physics and device application.

Significance in terms of fundamental physics includes the fact that fundamental difference in the action of magnetic field and current on the magnetic structure becomes clear, and it is a universal nature being independent of the material and microscopic structure. Also, the general understanding on the creep motion of elastic interfaces becomes deepened. This is expected to give important insight upon the understanding of the motion of magnetic flux in type II superconductors and so on.

Significance in terms of device application includes the fact that important insights for the development of magnetic domain wall motion devices were obtained. Previous studies showed that the thermal stability[*3] of domain wall is determined independently of the critical driving current in case that the domain wall is driven by adiabatic spin-transfer torque; this property is favorable for the applications. From the present study, the way to design the material so that the adiabatic spin-transfer torque effectively acts on the domain wall becomes clear, which is expected to further facilitate the device development.

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<Figures>

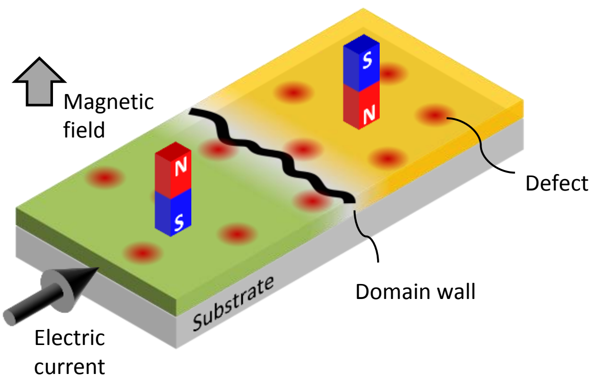

Fig. 1: Schematic of sample. Magnetic domain wall formed at the boundary between two domains having opposite magnetization direction moves very slowly under the application of magnetic field or electric current.

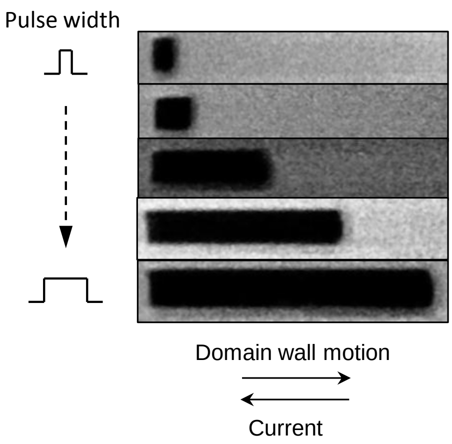

Fig. 2: Example of observation result of the change in magnetic structure induced by current pulse. The region swept by domain wall is visualized by a microscope with a magneto-optic effect. As the pulse width increases, the displacement of domain wall becomes long.

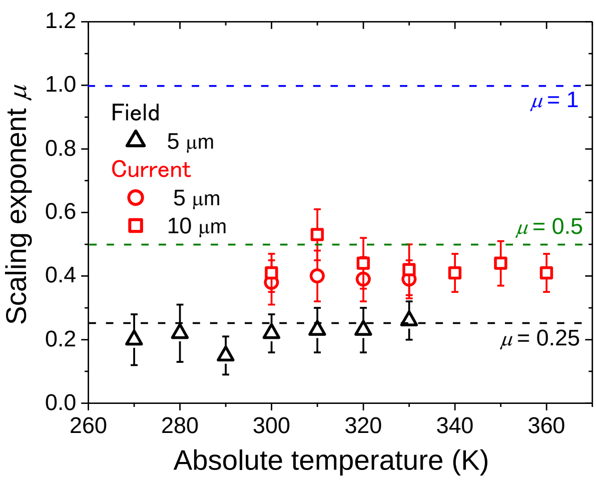

Fig. 3: Device temperature dependence of the scaling exponent for the field and current-induced domain wall creep. For the current-induced creep, samples with the width of 5 and 10 μm were used. Scaling exponent independent of temperature and wire width indicates the universality. Horizontal broken lines indicate the theoretically known scaling exponent μ (= 0.25, 0.5, 1).

<Notes>

*1: Magnet-optic effect

Phenomena in which the polarization of transmission or reflection light is changed due to the magnetic state of the material or applied magnetic field.

*2: Adiabatic spin-transfer torque

A torque acting on magnetization through the adiabatic transfer of the spin angular momentum of conduction electron to the angular momentum of orbital electrons.

*3: Thermal stability

An index to represent how stably the system can retain the state under the thermal fluctuation.

<Paper information>

S. DuttaGupta, S. Fukami, C. Zhang, H. Sato, M. Yamanouchi, F. Matsukura, and H. Ohno
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For inquiries:
*About the research
Shunsuke Fukami, Associate Professor
Center for Spintronics Integrated Systems, Tohoku University
E-mail: s-fukami <at> csis.tohoku.ac.jp
*About the press
General Affairs Section
Research Institute of Electrical Communication, Tohoku University
E-mail: somu <at> riec.tohoku.ac.jp