博士論文（要約）

Unidirectional magnetoresistance and spin-orbit torque in ferromagnetic thin films

（強磁性薄膜における
一方向性磁気抵抗とスピン軌道トルク）

長谷川　顕登

Introduction

Spintronics is the electronics that uses the spin degree of freedom of electrons, and it has been advanced since the discovery of the giant magnetoresistance effect. Today, magnetic storage devices play a crucial role in coping with the burgeoning explosion of information. In recent years, magnetic random-access memory is being developed as a next-generation technology that can achieve high endurance, reliability, and speed. These spintronic devices exploit the magnetoresistance effect, and hence magnetoresistance is a central research topic in the field of spintronics. The recently discovered unidirectional magnetoresistance (UMR) is a phenomenon in which the resistance depends on the current direction. Notably, the unidirectional spin Hall magnetoresistance (USMR) in a nonmagnetic metal/ferromagnetic metal heterostructure is understood as a resistance change that depends on the relative angle between the magnetization and spins injected into the ferromagnetic layer by the spin Hall effect, where the polarization direction of the injected spin gets reversed with the reversal of current direction. However, the detailed physical origin of USMR is still unclear. Furthermore, research on UMR in ferromagnetic thin films has been limited almost exclusively to nonmagnet/ferromagnet heterostructures. In this thesis, we first studied the UMR originating from the spin Hall effect using a standard nonmagnetic metal/ferromagnetic metal structure to obtain a better understanding of the USMR. Then, using a structure different from a conventional nonmagnet/ferromagnet structure, we aimed to detect UMR originating from another charge-to-spin conversion than the spin Hall effect. We also investigated the spin-orbit torque (SOT) because SOT has a close relationship with the spin injection into a ferromagnet.

Tunable unidirectional spin Hall magnetoresistance in ferrimagnetic CoGd films

The spin-dependent conductivity in ferromagnets has been proposed as one of the origins of USMR. When spins are injected into a ferromagnetic layer by the spin Hall effect, the numbers of majority and minority spins are modulated depending on the relative angle between the injected spins and the magnetization. The combination of this modulation and the spin-dependent conductivity leads to a resistance change. This mechanism is deemed to be considerably similar to the giant magnetoresistance effect in ferromagnet/nonmagnet/ferromagnet heterostructures, where the resistance is determined by the spin-dependent conductivity and the relative angle between the two magnetizations. Although such a similarity has been highlighted since the discovery of USMR, there have been few studies using this similarity to control USMR. In this study, we focus on the sign reversal of the giant magnetoresistance around the compensation point in ferrimagnets and investigate the USMR in nonmagnet (W)/ferrimagnet (CoGd alloy) structures. As a result, USMR is found to reverse its sign around the compensation composition and temperature. This sign reversal emphasizes the importance of spin-dependent conductivity in determining USMR.

Enhanced unidirectional spin Hall magnetoresistance in a Pt/Co system with a Cu interlayer

Spin dependence of conductivity exists not only inside a ferromagnetic layer but also at a nonmagnet/ferromagnet interface. In the previous studies, the bulk and interface contributions were not separated. In this study, we investigate the role of interfacial contribution through the control of an interfacial structure of a nonmagnet/ferromagnet system. Specifically, we evaluate the USMR in Pt/Cu/Co systems because the Cu/Co interface is well known to exhibit a strong spin-dependent scattering, and thus large giant magnetoresistance. Importantly, the USMR increases up to 1.5 times by inserting a Cu layer into a Pt/Co interface. By investigating the effect of Cu insertion on SOT and the Cu thickness dependence of USMR, we conclude that the enhancement of USMR is owing to the strong spin-dependent scattering at the Cu/Co interface. This result is also consistent with the scenario that the USMR originates from the spin-dependent scattering.

Unidirectional magnetoresistance induced by spin planar Hall effect

In previous studies of UMR in ferromagnets, nonmagnets have been mainly employed as a source of spin current. However, if the essence of UMR is spin injection and spin-dependent conductivity, source of spin current does not necessarily have to be nonmagnets. Here, we report a new type of UMR that originates from the charge-to-spin conversion in a ferromagnetic metal, where spin current is generated with the same angular dependence as the planar Hall effect. We also propose a theory of the UMR due to this novel charge-to-spin conversion, hereafter denoted as spin planar Hall effect, by solving the spin diffusion equation. By comparing the obtained theoretical expression with the experimental results, the charge-to-spin conversion efficiency of the spin planar Hall effect in NiFe is found to be comparable to that of the spin Hall effect in Pt. Our findings extend the versatility of UMR as a method to detect the spin current and contribute to the elucidation of novel charge-to-spin conversion phenomena.

Current-induced perpendicular magnetization switching without external magnetic field in an asymmetrically gated structure

In addition to the planar Hall effect described above, various methods have been proposed to generate spins with different polarization than the spin Hall effect. One of them is the generation of a perpendicularly polarized spin current via Rashba-Edelstein effect in a structure with lateral asymmetry. This spin current is fascinating because it enables the field-free perpendicular magnetization switching. In this study, we focus on this emergent spin current because it could manifest itself as a distinctive angular dependence of UMR. As a first step, we demonstrate the field-free SOT magnetization switching in the laterally asymmetric structure, where the asymmetry is introduced by applying a gate voltage to only half side of a wire. In addition, we investigate the origin of this field-free magnetization switching by using transport measurement and magneto-optical imaging.