【Grant-in-Aid for Scientific Research (S)】

Investigation of orbital symmetry effect in spin-orbit torque and development for energy-efficient and high-density spin memory devices

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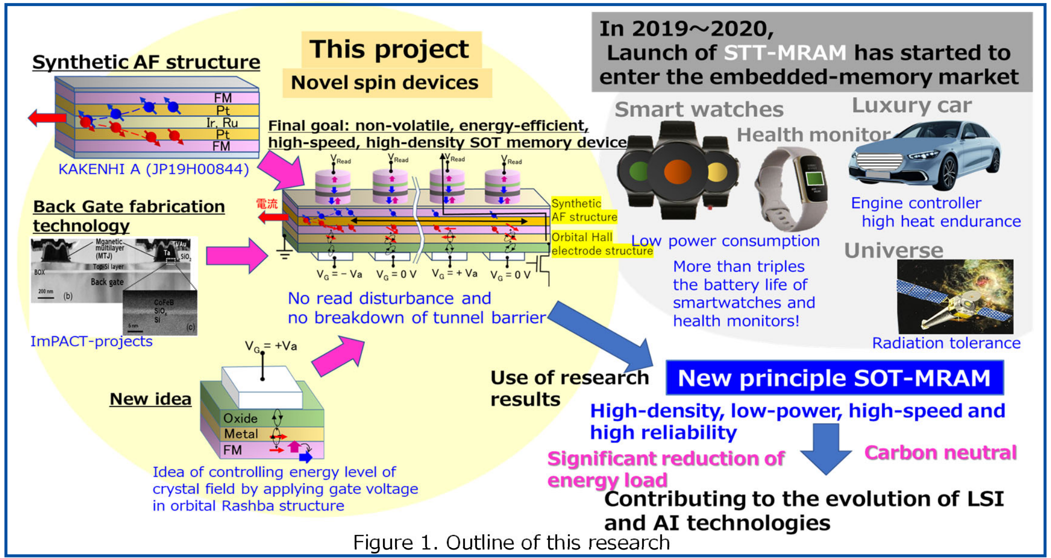
Project Information	Project Number : 24H00030　　Project Period (FY) : 2024-2028 Keywords : spin Hall effect, orbital Rashba effect, voltage effect, synthetic antiferromagnet, Dzyaloshinskii-Moriya interaction

Purpose and Background of the Research

●Outline of the Research

Developments of innovative green technologies are required to achieve carbon neutrality by 2050. On the other hand, recent rapid growth of artificial intelligence has led to an exploding of amount of information, and an increase in power consumption has become a serious problem. Given these recent circumstances, it is necessary to realize nonvolatile memory devices with energy-efficient, high-speed, and high-density, so as to reduce power consumption of large-scale-integration (LSI) significantly.

The purpose of this research is to create energy-efficient, high-speed and high-density spin memory devices for LSI. To achieve energy-efficient spin memory devices, increase of the magnitude of spin orbit torque (SOT) originating from spin Hall and orbital Rashba (SH and OR) effects is important. Correlation between the magnitude of SH and OR effects and physical and structural properties will be investigated to clarify the spin conduction mechanism. Based on this mechanism, low-resistance and energy-efficient devices will be developed. Furthermore, in order to realize high-density, we will develop a technology for field-free switching of perpendicularly magnetized magnetic tunnel junctions (MTJs) and a voltage control technology for the OR effect. To achieve this, it is important to construct orbital current control technology by modulating the crystal field of oxides (or nitrides) and to design the nanostructure of materials. By integrating the above established technologies, non-volatile, energy-efficient, high-speed, high-density SOT memory device operation will be demonstrated. Through this research, we will contribute to a carbon-neutral society.



No read disturbance and no breakdown of tunnel barrier

Idea of controlling energy level of crystal field by applying gate voltage in orbital Rashba structure

Low power consumption

More than triples the battery life of smartwatches and health monitors!

High-density, low-power, high-speed and high reliability

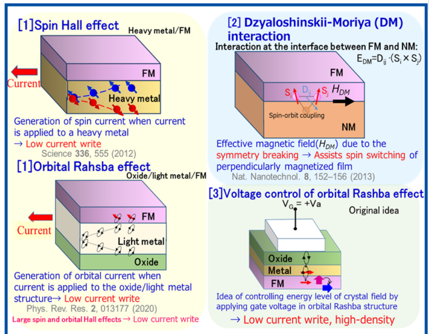
Significant reduction of energy load

Contributing to the evolution of LSI and AI technologies

Figure 1. Outline of this research

●Approach

High-quality and well-controlled films will be prepared by using our state-of-the-art atomic-scale thin film growth techniques. For understanding mechanisms, precise transport measurements and theoretical calculations on electronic structure and electronic transport in realistic heterostructures will be performed. Through our collective studies, we will achieve the non-volatile, energy-efficient, high-speed, high-density SOT memory device shown in Fig. 1 by addressing the scientific studies of the SH effect (upper left in Fig. 2), OR effect (lower left in Fig. 2), Dzyaloshinskii-Moriya (DM) interaction (upper right in Fig. 2) and the voltage control of OR effect (lower right in Fig. 2).



Generation of spin current when current is applied to a heavy metal → Low current write
Science 336, 555 (2012)

Generation of orbital current when current is applied to the oxide/light metal structure→ Low current write
Phys. Rev. Res. 2, 013177 (2020)

Large spin and orbital Hall effects → Low current write

Interaction at the interface between FM and NM: $E_{DM}=D_{ij}\cdot(S_i \times S_j)$

Effective magnetic field(H_{DM}) due to the symmetry breaking → Assists spin switching of perpendicularly magnetized film
Nat. Nanotechnol. 8, 152–156 (2013)

Idea of controlling energy level of crystal field by applying gate voltage in orbital Rashba structure
→ Low current write, high-density

Figure 2. Physical phenomena to be studied in this research

Expected Research Achievements

This research introduces new ideas into SOT-MRAM to create reliable technologies for realizing energy-efficient, high-speed and high-density LSI and artificial intelligence (AI) devices. Specifically, through this research, we will achieve the following 4 technologies.

●Construction of highly efficient writing technology using SH and OR effects

In this study, we use the two original structures shown in Fig. 3. We have found that the synthetic antiferromagnetic (AF) structure shown in the left figure of Fig. 3 is a promising structure because it provides a large spin Hall angle θ_{SH} (small write current) with a small resistivity ρ_{xx} which are close to the write energy specification after 5 years. Here, we will elucidate the mechanism by which large θ_{SH} is obtained and further improve those properties (θ_{SH} > 50% and ρ_{xx} < 50 μΩcm).

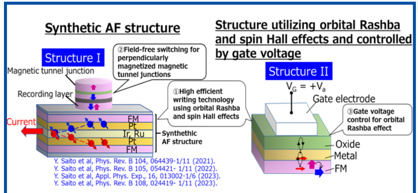


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Figure 3. Two structures addressed in this study

●Field-free switching for perpendicular MTJs

We have found that ferromagnetic (FM) layers in perpendicular magnetized synthetic AF structures can be field-free switching by breaking the symmetry using a DM interaction acting parallel to the interface between FM and nonmagnetic (NM) layers. Here, the magnitude of the DM interaction will be investigated in detail, and the nanostructure of the interface will be optimized using Landau-Lifshitz-Gilbert simulation to achieve both large θ_{SH} and field-free switching.

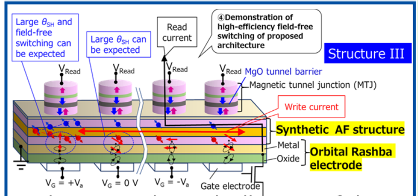

Figure 4. Schematic diagram of the original architecture

●Gate voltage control technology for OR effect

The OR effect is thought to originate from an orbital current generated at an interface such as oxide (or nitride) that is energy-separated by the crystal field. Considering this, it is expected to be possible to control the energy level of the crystal field by applying a voltage to the oxide (or nitride) and modulating the potential of the Fermi surface with a gate voltage (right figure of Fig. 3). We will demonstrate this original idea.

●Demonstration of high-efficiency field-free switching of the proposed architecture

The original architecture shown in Fig. 4 achieves high-density by arranging many MTJs on a single wiring. Moreover, in this architecture, batch writing is expected to reduce power consumption significantly. We will demonstrate this idea.

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