【Grant-in-Aid for Transformative Research Areas（B）】

A study of novel colossal interface responses induced by super orbital splitting

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Research Area Information	Number of Research Area : 23B202　Project Period (FY) : 2023-2025 Keywords : Super-orbital splitting, Oxide heterostructures, Multiferroics, Electron microscopy, Multi-scale simulation	

Purpose and Background of the Research

●Outline of the Research

Recently, researchers in this group have observed giant magnetization responses triggered by an electric field at interfaces between different materials, such as oxides and metals. These responses were not predicted by existing theories. These phenomena are believed to arise from a unique form of orbital splitting termed "super orbital splitting," which remains only partially understood based on current research. These discoveries hold the potential to enable the development of highly efficient devices. Simultaneously, they indicate the presence of unexplored phenomena at hetero-interfaces of diverse material systems. In this realm of research, our goal is to establish the field of "interface science." This field aims to produce novel functionalities that can lead to the realization of exceptionally efficient devices. We achieve this by conducting thorough investigations into how external fields (electric and magnetic) induce responses in various physical properties, such as magnetization, spin, and structural changes, across a range of interfaces. Through an iterative research approach, we plan to uncover new phenomena and material systems. This process involves atomic-scale observations of these phenomena, theoretical comprehension via first-principles calculations, and feeding these insights back into experiments. By comprehending the physics underlying super orbital splitting and effectively controlling it at the interfaces of heterostructures, we aspire to establish a pioneering academic discipline. This discipline will serve as a foundation for achieving colossal responses driven by external fields.

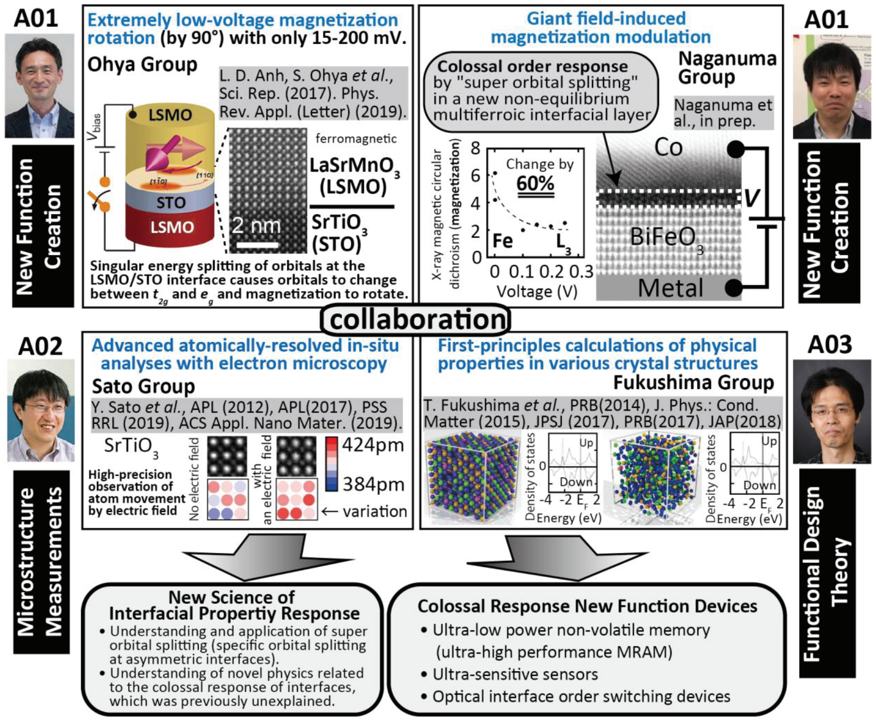

Figure 1: Overview of this research area

The giant magnetization responses generated by an electric field, as recently observed by our members, are believed to arise from a unique super orbital splitting occurring at interfaces (depicted in Fig. 2). This phenomenon was scarcely anticipated until now. These findings imply the existence of numerous unknown giant response phenomena, induced by external fields, hidden by bulk signals at interfaces between dissimilar materials. In this study, our objective is to unravel the origins of these newfound phenomena, employing both experimental and theoretical approaches. Additionally, we aspire to pioneer novel functionalities and revolutionize established academic domains by creating innovative interfaces that trigger orbital splitting, leading to colossal responses. Consequently, this field embodies ambitious aspirations, seeking to establish novel academic and industrial domains rooted in entirely original concepts that extend beyond the confines of existing academic disciplines.

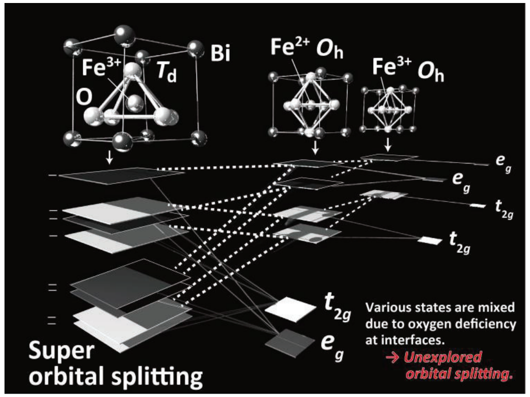

Figure 2 Concept of the Super-Orbital Splitting

Expected Research Achievements

Research Contents

Through close collaboration among our groups, we pioneer innovative research fields as below. Our ultimate goal is to establish novel interface structures with colossal responses.

- □ Theoretically elucidating peculiar orbital splitting at oxide interfaces and comprehending the relationship between orbital states and magnetic anisotropy.
- □ Measuring structural displacements in non-equilibrium interface multiferroic layers and theoretically understanding their super orbital splitting.
- □ Predicting and exploring interfaces exhibiting giant responses, coupled with measurements of external field-induced structural displacements and electron energy loss spectroscopy.
- □ Realization of novel interfaces with colossal responses.

Ripple effects of Our Research

- □ Realizing low-power magnetization reversal techniques will introduce an innovative data rewriting technology with ultra-low energy consumption. This advancement holds potential to supplant semiconductor devices with spin devices and greatly enhance the efficiency of information processing technology.
- □ The sensitivity of ultra-compact magnetic sensors will witness significant enhancement. Applications like MRI and MEG, prevalent in bio-magnetic sensing, could be replaced by giant interface-responsive devices. The need for helium cooling will be eliminated, leading to substantial cost reduction in medical diagnostics.
- □ This new scientific approach in our field seeks to pioneer novel physics by delving into interface structures and electronic states on an atomic level. This will stimulate the exploration of interfacial structures using diverse techniques such as light, X-ray, neutron, and electron beams. Our research is poised to attract engagement from other scientific domains.
- □ The material design methodology within this research, capable of accounting for finite temperature effects (magnon and phonon scattering), which have been traditionally overlooked in first-principles calculations, can be extended to the creation of other energy-efficient and energy-generating materials.

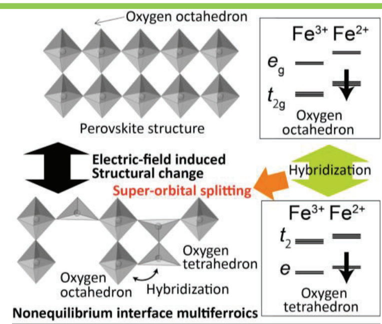

Figure 3 Mechanism of super-orbital splitting in non-equilibrium interfacial layers. Fe^{2+} and Fe^{3+} atoms are mixed due to oxygen deficiency. In these non-equilibrium interface multiferroics layers, four different states with two orbitals are mixed, resulting in the formation of up to 16 (=2^4) orbitals.

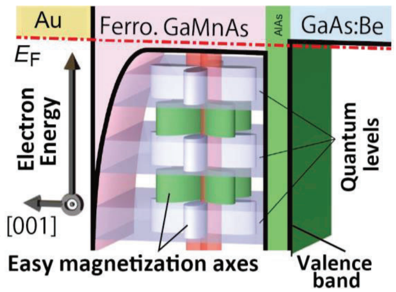

Figure 4 Change in magnetic anisotropy symmetry at quantum levels in a ferromagnetic semiconductor quantum well structure [Nature Commun. (2016) (2017)] and realized the possibility of controlling the orientation of magnetization.

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