Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp37-38

# Microscopic Mechanism of the Electric-Field Effects on Spintronics Devices Elucidated by X-ray Magnetic Circular Dichroism Spectroscopy

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**Abstract**

**We used X-ray magnetic circular dichroism (XMCD) spectroscopy to investigate the microscopic origin of the voltage-controlled magnetic anisotropy in a ferromagnetic metal/dielectric junction. We quantitatively determined the voltage-induced change in the magnetic moments as well as valence electronic states of the specified element with an extremely high sensitivity. Based on our experimental and first-principle calculation results, we revealed that two different mechanisms are dominant in the electric-filed modulation of the magneto-crystalline anisotropy energy of the system.**

## 1. Introduction

Controlling the magnetic anisotropy in ferromagnetic thin films by voltage application is an intriguing phenomenon [1, 2]. This effect has attracted much attention because of the richness of underlying physics as well as the potential applications for nonvolatile magnetic memories of extremely low power consumption. Various approaches have been conducted for searching new materials to further enhance the voltage effect. Among these, voltage-induced magnetic effects involving a purely electronic process (no chemical reaction accompanied) in fully solid-state devices are of technologically high importance because such phenomena are desirable for real applications for memories with a high-speed operation and long-term endurance. To this goal, to clarify the microscopic mechanism of the voltage-induced magnetic anisotropy is another important issue. Experimental techniques to directly observe the key electronic states and the magnetic moments are strongly required. In this study, we developed high-resolution X-ray spectroscopy techniques using synchrotron radiation to elucidate the origin of the electric-filed effects [3–7]. From the results, we propose possible microscopic mechanisms for two typical systems, Fe/Co/MgO and $L1_0$-FePt/MgO, for which the 3*d* and 5*d* elements take an important role, respectively.

## 2. In-situ XMCD spectroscopy with unprecedented accuracy

We performed X-ray absorption spectroscopy experiments using the soft and hard X-ray beamlines at SPring-8. We developed *in-situ* X-ray magnetic circular dichroism (XMCD) measurements in the fluorescence detection mode under conditions of a bias voltage applied. Figure 1(a) shows an experimental setup of the XMCD measurement. The sample was a multilayer film grown on a MgO substrate, which has a junction structure consisting of a ferromagnetic metal film with the thickness of a few atomic layer, a dielectric MgO layer, and electrodes on the top of the insulating layer. A circularly polarized X-ray beam was incident on the sample in the direction normal to the film plane, and magnetic field

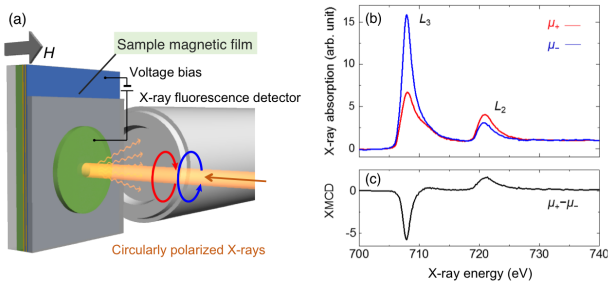


Fig. 1 (a) Schematic of the experimental setup of X-ray magnetic circular dichroism (XMCD) spectroscopy. (b) Typical X-ray absorption (XAS) and (b) XMCD spectra in Fe/MgO film at the Fe $L_{2,3}$ edge [3].

was applied in the direction parallel to the X-ray direction. The photon energy of incident X-rays was tuned to the absorption edge of the magnetic element so as to excite the core-level electrons to the valence states that are relevant to the magnetism. Figure 1(b) shows typical X-ray absorption spectra (XAS) at the Fe $L_{2,3}$ edges. In Fig. 1(c), the XMCD spectra is defined by $\Delta\mu = \mu^+ - \mu^-$, where $\mu^+(\mu^-)$ is the XAS (detected by monitoring X-ray fluorescence intensity) for right- and left-circular polarization.

Voltage-induced changes in XMCD intensity was assumed to be less than 0.5%, which required extremely high detection accuracy which had never been achieved using the fluorescence detection. To improve the accuracy in XMCD measurements, we constructed new spectrometer systems with large-area and multi-element silicon drift detectors at hard (BL39XU) and soft X-ray beamlines (BL25SU) of SPring-8. At BL39XU, the standard errors of XMCD data were reduced by a factor of three compared with the previous system, which was the result of more than ten-times increase of the detection efficiency in our new system. Another detection system installed at BL25SU worked well, and the statistics of soft-X-ray MCD spectra has been improved greatly.

## 3. Microscopic mechanism of voltage-induced magnetic anisotropy

We studied $L1_0$-FePt/MgO and Fe/Co/MgO junctions to determine the voltage-induced changes in the element-specific orbital and spin magnetic moments, and the magnetic dipole terms of the relevant elements. For a Fe/Co/MgO, we successfully observed clear voltage-induced change in the XMCD amplitude of ±0.2% at electric fields of ±0.18 V/nm [4]. Change in the anisotropy of orbital magnetic moment of Co was determined to be $0.017\mu_B$ between magnetization directions of out-of-plane and in-plane. According to the Bruno model [8], the voltage-induced change in the magnetocrystalline anisotropy energy (MAE), *i.e.* difference in the spin-orbit coupling energy, was estimated and was in excellent agreement with the result obtained by ferromagnetic resonance measurement. The voltage-induced change in the Co orbital magnetic moment is concluded to be the major origin of the electric-field effect at the Co/MgO interface.

In an $L1_0$-FePt/MgO junction, XMCD spectra at the Pt $L$ edges showed reversible and repeatable changes by application of bias voltage of ±0.7 V/nm [5]. The interfacial Pt atoms were found to be responsible for the voltage effect. The magnetic dipole $\langle T_z \rangle$ term of the Pt 5*d* electrons remarkably increased at a negative bias voltage, enhancing the MAE through the induction of electric quadrupole moments and the spin-flip excitation [5]. In contrary, changes in the Pt orbital magnetic moment has not been detected within the experimental resolution.

By an EXAFS analysis in a similar Fe/Pt/MgO junction with a monatomic Pt layer, the changes in the atomic distance between the interfacial Pt and neighboring atoms were shown to be less than 0.01 Å [6]. The EXAFS results suggested the purely electronic mechanism of voltage-induced anisotropy without lattice deformation or atomic migration.

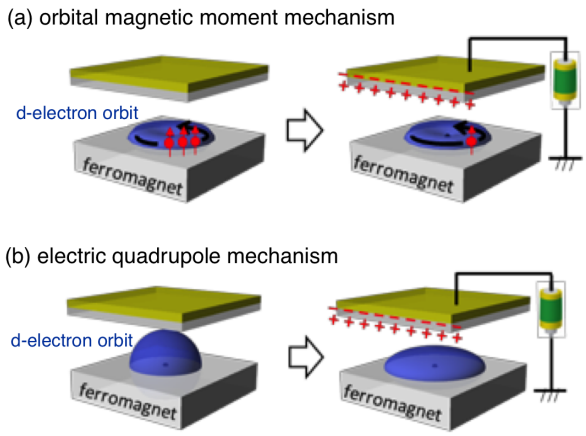


Fig. 2 Two different microscopic mechanism of electric filed d effects for magnetic anisotropy [7]. (a) Orbital magnetic moment mechanism and (b) electric quadrupole mechanism.

Figure 2 compares two mechanisms that we found to be the microscopic origin of the voltage-induced magnetic anisotropy [7]. In the Fe/Co/MgO system, the change in the orbital magnetic moments by the external voltage is responsible to the voltage-induced MAE. This is mechanism is well explained by the Bruno model. On the other hand, in the $L1_0$-FePt/MgO system, the change in the magnetic dipole moment gives significant contribution to the voltage-induced MAE.

## 4. Conclusion

Our XMCD study directly demonstrated the voltage-induced changes in the element-specific magnetic moments. We proposed two different microscopic mechanism of electric-field effect in magnetic anisotropy. Well-known Bruno model was applicable to the Co/MgO interface, and electric quadrupole mechanism was relevant to the Pt/MgO interface. We stress the importance of the different electronic state between these two systems, particularly the magnitude of exchange energy and spin-orbit coupling. It should be pointed out the effectiveness of 5*d* elements with a large spin-orbit coupling, such as Pt and Ir [9], for producing devices with a further enhanced voltage-controlled magnetic anisotropy.

## Acknowledgements

The synchrotron radiation experiments were performed at SPring-8 with the approval of JASRI. This work was partly supported by JSPS KAKENHI (18H03880, 26103002, 17H02823) and the ImPACT program of the Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

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