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# Detecting modulation of orbital magnetic moments and magnetic anisotropy in $Co_2FeSi$ /PMN-PT via *Operando* X-ray magnetic circular dichroism

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Combining ferromagnetic and ferroelectric properties has been investigated as multiferroics, which provides considerable advantages of magnetization control by an electric field ($E$) as a low-energy power consumption operation without electric current. As spintronics research pursues the suppression of power consumption for device operations, the manipulation of the spins by $E$ is one of the solutions for future device applications. Recent developments have focused on the modulation of magnetization by a low electric field. Recently, a study reported that $Co_2FeSi$ / $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) interfacial multiferroics exhibited a giant magneto-electric (ME) effect of $1.8 \times 10^{-5}$ s/m [1], where $Co_2FeSi$ (CFS) is a Co-based Heusler alloy that was expected to have high spin polarization at room temperature and high Curie temperature. The origin of the large ME effect in CFS-based interfacial multiferroics was associated with strain-mediated magnetic anisotropy modulation. However, the microscopic origin of the giant ME effects in the CFS/PMN-PT interfacial multiferroics is still unknown. To initiate novel research into the physics of the relationship between the lattice distortion and orbital magnetic moments ($m_{orb}$), the anisotropic $m_{orb}$ needs to be explored even in interfacial multiferroics [2]. Since *operando* X-ray magnetic circular dichroism (XMCD) can probe element-specific orbital modulation when a reversible strain is applied, we developed the XMCD system with applying $E$.

X-ray absorption spectroscopy (XAS) and XMCD measurements of the Fe and Co $L$-edges were performed using the KEK-PF BL-7A beamline, Japan, at room temperature. A magnetic field was applied along the incident polarized soft X-rays along the normal direction of the surface of the sample. The electrodes were mounted on the surface of the sample and the rear of the substrate to perform the $E$-induced XMCD measurements [3].

Figure 1 shows the Fe and Co $L$-edge XAS and XMCD spectra obtained in the partial fluorescence yield mode under an applied electric field $E$ of $\pm$0.8 MV/m. The sample surfaces were connected to the ground, and $E$ was applied to the back side of the PMN-PT substrates. The XAS spectral line shapes originated from metallic Fe and Co features in CFS. The spectral line shapes of XMCD and the slight change in the $L_3$-edge peak were modulated by $E$ only at the Fe $L$-edge, despite the fixed sample measurement position. These results indicated that the $m_{orb}$ were modulated by the applied $E$, thereby resulting in changes in magnetic anisotropy. The modulation of $m_{orb}$ by 0.01 $\mu_B$ under an applied $E$ was related to the induced lattice distortion from the PMN-PT substrates. In contrast to the case of Fe, no spectral changes were detected for the Co $L$-edge XMCD [4].

The element-specific XMCD hysteresis curves at the Fe and Co $L_3$-edges during the application of $E$. In the case of +0.8 MV/m, easy axis behavior was clearly observed, whereas the −0.8 MV/m case indicated the hard axis. This result showed reproducible behavior of the changes in the magnetic easy-axis direction. In the case of Fe shown in Fig. 1c, the vertical axis strength was slightly different between $\pm$0.8 MV/m, thus affecting the changes in XMCD in the Fe $L_3$-edge intensity, whereas the hysteresis curves of Co by $\pm$0.8 MV/m overlapped above the saturation magnetic fields (Fig. 2d). Therefore, only the change in $m_{orb}$ for Fe was experimentally found [4].

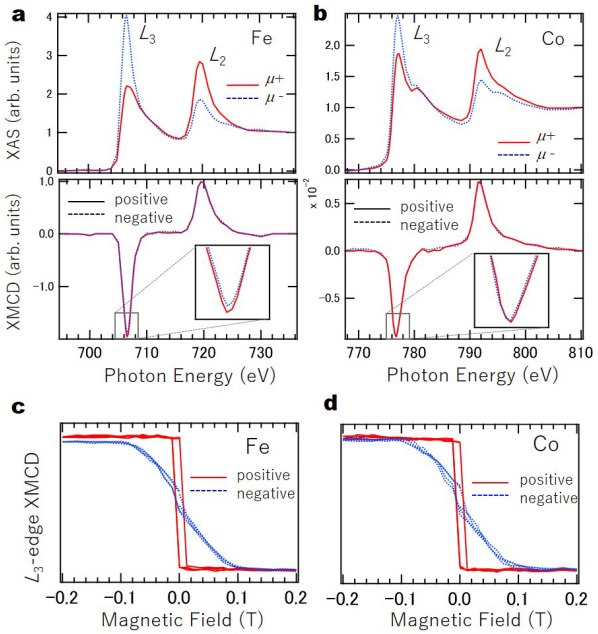


Fig. 1, XAS and XMCD under an applied electric field in $Co_2FeSi$/PMN-PT. (**a**) Fe and (**b**) Co $L$-edges at $\pm$ 0.8 MV/m. Expanded views around $L_3$ edges are shown in the bottom panels. Magnetic field dependence of $L_3$-edge XMCD under an applied electric field. (**c**) Fe and (**d**) Co $L$-edges at $\pm$ 0.8 MV/m [4].

## References

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