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Microscopic origin of magnetostriction in Fe_3Ga studied by *operando* XMCD

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The large magnetostriction (MS) effect has garnered attention for device applications involving sensors or vibrational power generation [1]. Although most significant MS effects depend on materials containing rare-earth elements, Fe_3Ga (Galfenol) modifies Fe-based materials to achieve a large MS of 300 ppm, which is ten times greater than that of conventional alloy compounds. However, the reason for the large MS in Fe_3Ga remains unclear. The doping of Ga atoms into pure bcc-Fe enhances the MS by altering the electronic structures [2]. The piezoelectric control of Fe_3Ga/ferroelectric materials has also gained interest through the introduction of reversible strain. From the perspective of electronic structures, the spin and orbital states under applied reversible strain must be examined. We have developed electric field (E)-induced operando x-ray magnetic circular dichroism (XMCD) technique to apply E to the ferroelectric substrate $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT), which reversibly tunes the interfacial lattice constants of the Fe_3Ga magnetic layer [3]. In this study, we discuss the microscopic origin of inverse magneto-striction effects or orbital-elastic effects in Fe_3Ga concerning the orbital magnetic moments (m_{orb}) using E-induced XMCD. Furthermore, to investigate the strain propagation into the Fe_3Ga layer induced by the piezoelectric effect in PMN-PT, extended X-ray absorption fine structure (EXAFS) analysis at the Fe K-edge is utilized to comprehend the element-specific modulation of the lattice distances.

We prepared samples of a 10-nm-thick Fe_3Ga (422) layer grown on single-crystal PMN-PT(011) substrates, incorporating a 0.3-nm-thick Fe layer via molecular beam epitaxy. The E-induced modulation of the in-plane magnetic properties was characterized using X-ray absorption spectroscopy (XAS) and XMCD, while the structural modulation due to E was monitored through EXAFS. *Operando* XMCD and EXAFS measurements were conducted at BL-7A and 9A, respectively, in the Photon Factory (KEK). The partial-fluorescence-yield mode was employed for both experiments. To apply an E to the PMN-PT substrate along the [011] direction, a Au(100 nm)/Ti(3 nm) electrode was deposited on the backside of the PMN-PT substrate, with the Fe_3Ga film serving as the top electrode. For XMCD measurements, the photon helicity was fixed while the magnetic field and beam incidence direction were varied for both positive and negative values.

The magnetization measurements indicated that the magnetic easy axis is slightly altered when applying E due to the modulation of in-plane lattice strain of approximately 0.1% in PMN-PT. Figure 1 displays the XAS and XMCD under applying E. XAS line shape exhibits clear metallic shapes and XMCD at L_3 slightly modulated by applying E. This originates from the changes in m_{orb}. By applying an E of −8 MV/m, the magnetic-field dependence at L_3-edge shown in Fig, 1(c) clearly shows the changes of magnetic easy and hard axes direction. The saturation magnetization value increased in the magnetic-field dependence of Fe L-edge in XMCD spectral analysis. The variations in L_3-edge XMCD intensity arise from the in-plane lattice strain. The increase in m_{orb} due to E mirrors the phenomenon seen in Co_2FeSi/PMN-PT [4] and differs from that in Fe_3Si/PMN-PT. Given that the electronic structures in Fe_3Ga derived from band-structure calculations differ from those in Fe, m_{orb} in Fe_3Ga is influenced by strain, resulting in a significant MS effect in Fe_3Ga. Additionally, Fe K-edge *operando* EXAFS also detected the modulation of nearest neighbor distances in Fe sites. Mössbauer spectroscopy further confirms the modulation of m_{orb}. Therefore, applying reversible strain through E to Fe_3Ga allows for the monitoring of orbital striction, clarifying the microscopic origin of the significant MS effects in Fe_3Ga, which can only be detected by *operando* XMCD and EXAFS.

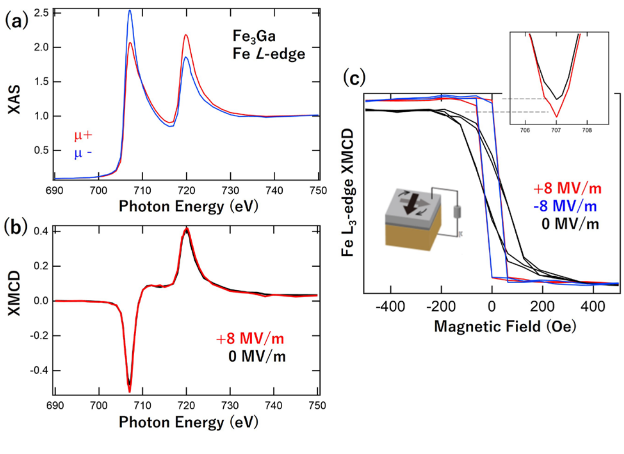

Fig. 1, XAS (**a**) and XMCD (**b**) under an applied electric field in Fe_3Ga/PMN-PT. (**c**) Magnetic-field dependence of Fe L_3-edge XMCD under an applied ***E*** of ± 8 MV/m with reversibly switching the applying electric field.

References
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