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Operando XMCD for magnetic anisotropy control by reversible strain at Fe_3Si/PMN-PT interface

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Artificial ferromagnetic/ferroelectric multiferroic heterostructures have been widely investigated from both fundamental and technological aspects. The electric field (***E***) control of magnetism through the interfacial strain modulates the magnetic anisotropy in the magnetic layer. Controlling the magnetic anisotropy by the interfacial strain related to the orbital (m_{orb}) or quadrupole (Q) moments has a potential for future devices using both spins and orbitals. The magnetic anisotropy (K) can be formulated by orbital moment anisotropy Δm_{orb} and Q,

$$K = \frac{1}{4}\xi \Delta m_{\mathrm{orb}} + \frac{\xi^2}{\Delta E} Q\langle S\rangle,$$

using spin-orbit coupling ξ, exchange splitting ΔE and spin $\langle S\rangle$ [1]. The relationship between strain and m_{orb} or Q has not been clarified because there were few tools to probe the changes of m_{orb} [2]. We have developed the ***E***-induced x-ray magnetic circular dichroism (EXMCD) technique in order to apply ***E*** to ferroelectric substrate $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT), which tunes the interfacial lattice constants of the Fe_3Si magnetic layer, which can be recognized as Fe substitution into Heusler alloy Co_2FeSi [3]. In this study, we discuss the microscopic origin of inverse magneto-striction effects or orbital-elastic effects concerning the m_{orb} and quadrupole moments by using the EXMCD.

We prepared the samples of 30-nm-thick Fe_3Si (422) layer grown on single-crystal PMN-PT(011) substrates with the insertion of 0.3-nm-thick Fe layer by molecular beam epitaxy. The ***E***-induced modulation of the in-plane magnetic properties was characterized by XMCD, where the XMCD measurement was performed at BL-7A in the Photon Factory (KEK). The partial-fluorescence-yield mode was adopted to probe the signals more than 10 nm below the sample surfaces. 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, where the Fe_3Si film was utilized as a top electrode [3,4].

The magnetization measurements revealed that the magnetic easy axis is along the PMN-PT $[01\bar{1}]$ in-plane direction at ***E*** = 0 kV/cm. By applying ***E*** of −8 kV/cm, the easy axis changes 90° along [100] direction within the in-plane through the changes of lattice strain of 0.1 % order. The Fe L_3-edge XMCD hysteresis curves also trace the same changes of magnetic anisotropy of 1.6×10^3 J/m^3. Interestingly, the electric field dependence of easy axis direction is opposite to the case of Co_2FeSi/PMN-PT [3]. Furthermore, the XMCD line shapes remain unchanged by applying ***E***, which corresponds to the changes originating not from m_{orb} but from the modulation of charge distribution forming quadrupole moments. Since the electronic structures in Fe_3Si deduced from the band-structure calculation are quite different from those in Co_2FeSi, m_{orb} in Fe_3Si is not scaled in linear relationship by strain unlike the case of Co_2FeSi [3]. These facts are affected to the ***E*** dependence in the XMCD line shapes. Therefore, applying reversible strain by ***E*** into Fe_3Si does not contribute to the orbital striction, which might be originated from the quadrupole modulation from two kinds of Fe site facing on Si atoms.

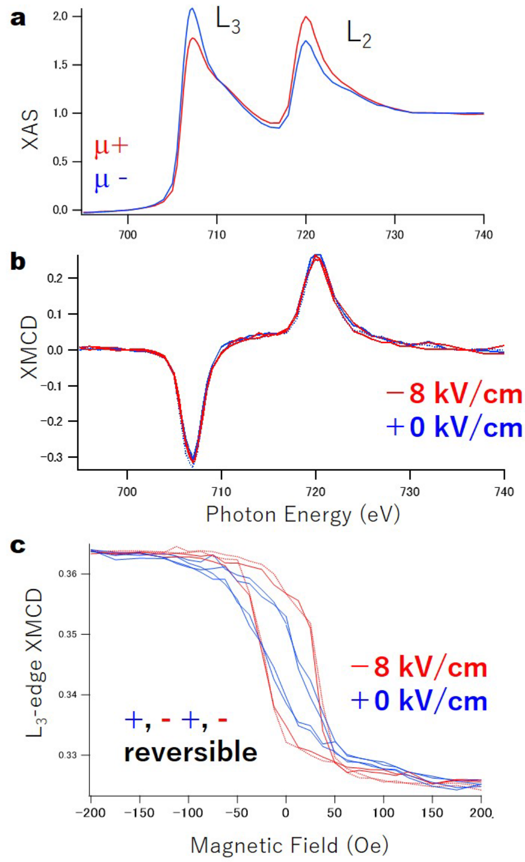

Fig. 1, XAS (**a**) and XMCD (**b**) under an applied electric field in Fe_3Si/PMN-PT. (**c**) Magnetic-field dependence of Fe L_3-edge XMCD under an applied ***E*** of ± 8 kV/cm with reversibly switching the applying electric field.

References
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