Relationship between Strain and Orbital Magnetic Moments in Ni/Cu Multilayers Studied by Electric-Field-Induced XMCD and First-Principle Calculation

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Controlling the magnetic anisotropy by the interfacial strain related to the orbital magnetic moments has a potential for future devices using both spins and orbitals. The relationship between strain and orbital magnetic moments has not been clarified because there were few tools to probe the changes of orbital magnetic moments. We have developed the electric-field (E) induced x-ray magnetic circular dichroism (EXMCD) technique in order to apply E to ferroelectric $BaTiO_3$ substrate, which tunes the interfacial lattice constants of the Ni/Cu multilayers on $BaTiO_3$ [1]. Since the domain structures in $BaTiO_3$ are modulated by E, EXMCD reveals that the changes of magnetic anisotropy in the Ni/Cu multilayer are induced by the modulation of orbital magnetic moments in Ni. In this study, we discuss the microscopic origin of inverse magneto-striction effects concerning the orbital magnetic moments by using the EXMCD and the first-principle calculation.

We prepared the samples of $[\mathrm{Cu}\ (9\ \mathrm{nm})/\mathrm{Ni}\ (2\ \mathrm{nm})]_5$ multilayers grown on [100]-oriented single-crystal $BaTiO_3$ substrates with thin Fe buffer layer insertion. The perpendicular magnetic properties were characterized by magnetization measurements and XMCD, which 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. An electric field was applied between the sample surfaces and the back side of the $BaTiO_3$ substrates. The first-principle calculation was performed using the Wien2K code including the spin-orbit interaction.

Without applying E, the Ni L_3-edge XMCD hysteresis curve showed perpendicular magnetic anisotropy because the tensile strains are introduced into the Ni layers. Under an applied E of up to ±2 kV/cm, the Ni L_3-edge EXMCD hysteresis curves changed from perpendicular to in-plane characteristics through the released lattice constants of 2 %. The EXMCD spectra and the first-principle calculations for the strained Ni also result in the linear relationship between the strain and the orbital moments. These phenomena can be understood within the orbital moment anisotropy through the spin-orbit interaction which is controlled by applying E. We found that EXMCD clarifies the origin of the reversible changes of perpendicular magnetic anisotropy and links the relationship between macroscopic inverse magneto-striction effects and microscopic orbital moment anisotropy.

[1] Y. Shirahata *et al.*, NPG Asia Materials **7**, e198 (2015).