"Orbital Elastic Effect" in Ni/Cu Multilayers on Ferroelectric $BaTiO_3$ Studied by Electric-Field-Induced XMCD

Controlling magnetic anisotropy related to interfacial strains has considerable potential for the development of future spin-orbitronics devices. We reversibly tuned the interfacial lattice constants of Ni/Cu multilayers on ferroelectric $BaTiO_3$ by applying an electric field (***E***). Since controlling the orbital magnetic moments of Ni is a key issue, we developed an electric-field-induced X-ray magnetic circular dichroism (EXMCD) technique. We clarified the origin of the reversible changes in perpendicular magnetic anisotropy and established the relationship between macroscopic magnetic anisotropy and orbital moments deduced from EXMCD as a concept of the "orbital elastic effect".

The coupling between ferromagnetic and ferroelectric properties has recently attracted considerable attention for the creation of novel devices by multiferroic control of their properties. In particular, the hetero-interfaces in thin films comprising both ferromagnets and electrically polarized materials produce a rich variety of possibilities for creating multifunctional properties. Modulation of interfacial lattice constants by an electric field (***E***) induces interfacial changes in magnetism. The interfacial lattice distortion produces variations in magnetic properties, which are recognized as inverse magnetostriction effects. Moreover, magnetic anisotropy is also tuned by lattice distortions. Recent attempts have focused on modulating the number of charge carriers at the interface between an ultrathin ferromagnetic layer and an oxide-barrier insulator in magnetic tunnel junctions. Other approaches, which we examined in this study, are based on interfacial mechanical strain coupling between ferromagnetic and ferroelectric layers using multiferroic hybrid structures. In this study, we focused on thin Ni layers sandwiched by Cu layers which exhibit perpendicular magnetic anisotropy (PMA) because of the interfacial tensile strain in the Ni layers.

In the Ni/Cu multilayers on $BaTiO_3$, the magnetization was switched from the perpendicular axis to the in-plane easy axis by tuning the lattice distortion through the application of ***E*** [1]. To understand this relationship and the elastic phenomena from the viewpoint of orbital magnetic moments, we developed a technique by applying ***E*** in X-ray magnetic circular dichroism measurements (EXMCD) to clarify the mechanism of the electric-field-induced changes in the magnetic anisotropy of Ni/Cu multilayers on $BaTiO_3$ hetero-structures through lattice distortions.

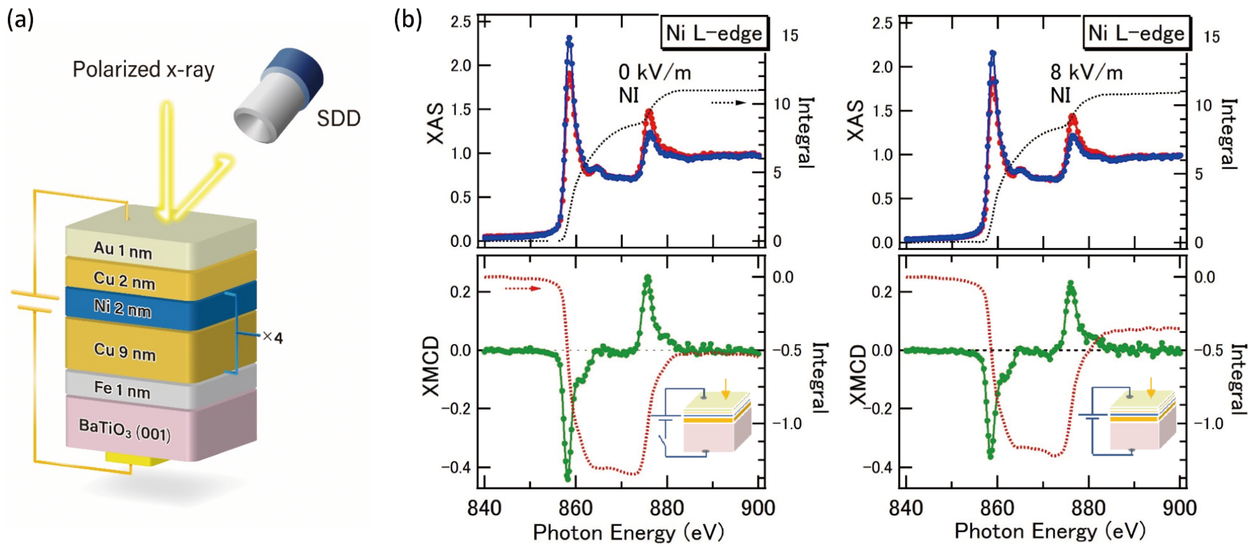

Figure 1: (a) Schematic structure of the sample. The electrodes for applying the electric field are mounted at the top (Ni/Cu layer) and the bottom ($BaTiO_3$ substrate) of the films. (b) XAS and XMCD spectra and their integrals obtained at Ni *L*-edges in partial fluorescence yield mode with and without an applied electric field.

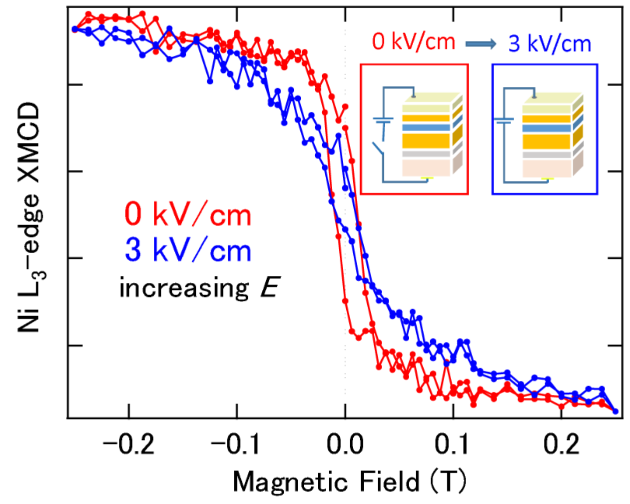

Figure 2: Element-specific magnetization curves for the Ni L_3-edge of EXMCD with and without applied ***E***.

The samples were grown by ultra-high vacuum molecular beam epitaxy on [100]-oriented $BaTiO_3$ single-crystal substrates. The stacked structures are shown in Fig. 1. The X-ray absorption spectroscopy (XAS) and XMCD measurements for the Ni and Cu *L*-edges were performed at the BL-7A beamline, at room temperature. The EXMCD measurements were performed using a special sample folder which enables the application of ***E*** under partial fluorescence yield mode and normal incident geometry.

Figure 1 also shows the Ni *L*-edge XAS and XMCD spectra by applying an electric field, ***E***, of positive bias of 8 kV/cm. Sample surfaces are connected to ground and *E* is applied to the back side of the $BaTiO_3$ substrates. The spectral line shapes of the XAS and XMCD are modulated by ***E***. By comparing the results with and without ***E***, we observed a slight variation in the peak asymmetries between the L_3 and L_2 edges. These results reveal that the orbital moments are modulated by applying ***E***, thereby resulting in changes of magnetic anisotropy. The values of spin and orbital moments are estimated to be 0.56 and 0.055 μ_B, respectively, for ***E*** of 0 kV/cm, and 0.56 and 0.045 μ_B, respectively, for ***E*** of 8 kV/cm. The modulation of the orbital magnetic moments by 0.01 μ_B upon applying ***E*** is related to the induced lattice distortion of 2% from the $BaTiO_3$ substrates. Moreover, after releasing ***E*** to zero, spectral line shapes also revert to the pristine state. Therefore, we conclude that the reversible changes of orbital magnetic moments are induced by lattice distortion, thus demonstrating a novel orbital elastic effect.

The element-specific magnetization curves (*M*–*H* curves) at the L_3-edge of Ni during the application of ***E*** are shown in Fig. 2. As the normal of the sample surface is parallel to both the incident beam and magnetic field, the contribution from the easy axis in PMA is observed. By applying ***E*** of ±8 kV/cm, the *M*–*H* curves change to those of the in-plane easy-axis behavior, which is related to the changes in the orbital magnetic moments in Ni. After switching off ***E***, the *M*–*H* curves exhibit the PMA characteristics again. Moreover, the reversible changes observed by applying ***E*** in XMCD are confirmed by the changes in the XMCD line shapes. The magnitudes of the changes in the *M*–*H* curves at the Ni L_3-edge XMCD are somewhat similar to those measured by the magneto-optical Kerr effect [1]. This phenomenon suggests that the domain structures in the observed area in the EXMCD measurements can be changed from the a-domain to the c-domain by applying ***E*** [2].

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