Development of Nanometer-Resolution Fluorescence-Yield Depth-Resolved Soft X-Ray Absorption Spectroscopy

Fluorescence-yield depth-resolved soft X-ray absorption spectroscopy (XAS), as well as X-ray magnetic circular dichroism, have been developed for observing the in-depth distribution of functional materials under the operando condition. Compared with the conventional electron-yield depth-resolved technique, it is capable of a wider range observation of in-depth magnetic distribution up to several tens of nanometers, and of operando measurements under electric and/or magnetic fields. By applying this technique to magnetic thin films, we obtained nanometer-resolution depth-resolved Fe L-edge XAS spectra for FeCo thin film, and a peculiar magnetic state of the interfacial Co layer was found for Co/GdO_x thin film.

Determination of the depth profile in thin layers has attracted much interest because the interface shows different properties from those of the bulk. Recent progress in fine processing technologies is increasingly manifesting the contribution of the interface to the properties of thin-film-based devices. In the case of magnetic thin films, the interface magnetism is usually estimated using the thickness dependence of the average magnetization over the whole film, based on the assumption that the interface magnetism is independent of the film thickness. Therefore, to directly observe the interface chemical and magnetic states, depth-resolved X-ray absorption spectroscopy (XAS) and X-ray magnetic circular dichroism (XMCD) techniques have been developed. The depth-resolved XAS enables determination of the depth profile of the chemical and magnetic states of magnetic thin films with sub-nanometer resolution [1, 2]. However, depth-resolved XMCD experiments are limited to investigation of the remanent magnetization because they are based on electron-yield detection, which is easily affected by external fields. Therefore, fluorescence-yield measurement is promising, and the fluorescence-yield depth-resolved soft X-ray XAS technique has recently been developed. We report here depth-resolved analysis for XAS spectra of FeCo thin film [3], and demonstrate the operando study of Co/GdO_x thin film [4].

All experiments were performed in high-vacuum chambers at beamlines BL-7A and BL-16A. A 4.3 nm-thick $Fe_{50}Co_{50}$ film was grown on a Ag(100) substrate by electron bombardment. In the soft X-ray region, XAS data are usually recorded in electron-yield mode. The probing depth, λ, of the XAS data is controlled by the electron emission angle since the effective escape depth of the emitted electron depends on its emission angle. Fluorescence-yield depth-resolved XAS measurement is based on the same principle as electron-yield measurement.

The experimental setup is shown in **Fig. 1(a)**. λ was estimated from the attenuation length, l, and the detection angle, θ_d, according to the relation $\lambda = l \cdot \sin\theta_d$. We arranged the configuration so that the lowest θ_d is set to 0.1°. By analyzing a set of XAS data at different values of λ, the depth-resolved XAS spectra can be obtained. The XAS spectra of the surface and inner layers are extracted by using the standard spectra for Fe metal, Fe_3O_4, γ-Fe_2O_3 and α-Fe_2O_3, in the fitting procedure. **Figure 1(b)** shows extracted Fe L-edge XAS spectra for the surface and inner layers of the FeCo thin film. The surface layer shows an oxide-like spectral shape, while the inner layer shows a metallic shape. The estimated ratio of the metallic component was 46% for the surface layer, while that of the inner layer was 88%, and the thickness of the surface layer was found to be 3.1 nm. We thus observed the in-depth distribution of the Fe chemical state in the FeCo film, with nanometer-depth resolution.

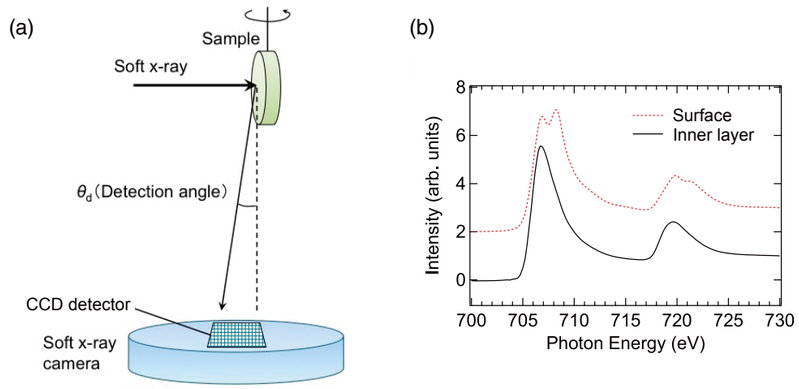

Figure 1: (a) Experimental setup for the fluorescence-yield depth-resolved XAS measurement and **(b)** extracted Fe L-edge XAS spectra for the surface and inner layers of the FeCo thin film.

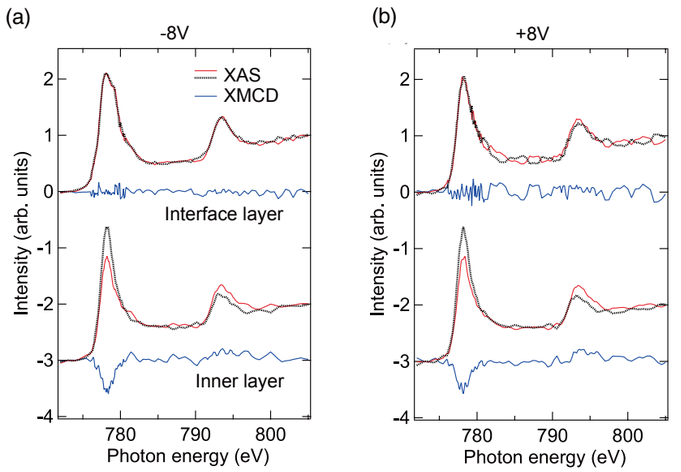

Figure 2: Layer-resolved Co L-edge XAS and XMCD spectra for Co/GdO_x thin film at the applied voltages of **(a)** –8 V and **(b)** +8 V.

Depth-resolved measurement under an electric field was performed for a Co/GdO_x thin film. It was reported that the magnetic anisotropy in Co is changed by the electric field. To understand the field-induced effect, it is important to directly observe the magnetic states at the interface. Five nm-thick Au and 2 nm-thick Co layers were grown on a (0001) sapphire substrate by electron bombardment, and then 5 nm-GdO_x was prepared by reactive evaporation of Gd with O_2. The XMCD spectra were taken at the grazing incidence condition because the film showed in-plane magnetization. The voltage was applied between the film surface and the bottom Au electrode. In a similar manner with the FeCo case, the Co L-edge XAS and XMCD spectra for the Co/GdO_x thin film at ±8 V were extracted, as shown in **Fig. 2**. The XMCD signal of the interface layer is considerably small for both voltages compared to that in the inner layer, which indicates that the field-induced magnetic change does not depend on the interface magnetism but on the inner layer. Therefore, direct observation of the interface magnetic state under the electric field was successfully demonstrated, though detailed structural analysis is required for further understanding of the field-induced effect.

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BEAMLINES

BL-7A and BL-16A

M. Sakamaki and K. Amemiya (KEK-IMSS-PF)