High-magnetic-field soft X-ray spectroscopy using a 30 T pulse magnet

Magnetic materials are generally synthesized and used as alloys and compounds. They are also stacked as a multilayer film for spintronics device such as a reading-head sensor of a hard disk drive. The evaluation of magnetization is the most fundamental characterization in studies of magnetic materials. Magnetic field and temperature dependence of the magnetization gives rich information on magnetic properties including magnetic order and anisotropy. In alloys and compounds involving more than two elements, the partial magnetization originating from individual elements, which is called the element-specific magnetization, promises to provide a deeper understanding of their magnetic property.

X-ray magnetic circular dichroism (XMCD) in absorption spectroscopy is one of the magneto-optical effects and provides the element-specific magnetization, where element selectivity follows the selection rule of core-electron excitation. In particular, XMCD in the soft X-ray region have the inherent advantage of probing the 3*d* bands of transition metals and the 4*f* band of the lanthanoids. With the increasing popularity of XMCD, high magnetic fields have become more important for the study of magnetic materials by means of XMCD, in order to investigate paramagnetic, antiferromagnetic, and metamagnetic materials. The available magnetic field used for soft XMCD, however, has remained at 10 T for the last decade. In order to far exceed 10 T, the possibility of using a pulse magnet that provides a field over 20 T was considered. Although the total electron yield (TEY) method is the most used and the most convenient detection method for soft X-ray absorption measurements, it is anticipated that TEY detection might be strongly affected by large amounts of noise due to an eddy current. Nevertheless, the TEY method is crucial for the practical application of high-magnetic-field XMCD to not only transmittable thin films but also bulk and powder samples. By considering of the use of high-magnetic-field XMCD as a universal method in the future, we have decided to use the TEY method in high-magnetic-field XMCD experiments. In the present article, we introduce our attempts to measuring soft XMCD under pulsed high magnetic fields.

A new apparatus for high-magnetic-field XMCD measurements was installed at the soft X-ray beamline **BL25SU**, at which the helicity switching technique was developed using twin helical undulators. An ultra-high vacuum (UHV) chamber of the XMCD apparatus is shown in the schematic drawing in Fig. 1. A nondestructive pulse magnet capable of generating 30 T is mounted outside of the vacuum chamber and is directly cooled by liquid nitrogen. The duration of the pulse is about 50 ms. The TEY signal and the induction voltage from the magnetic field are simultaneously recorded with a frequency of 1 MHz. XMCD ($\mu_m(H)$) is given by the difference in the magnetic field dependence of the absorption profiles for the plus (h_+) and minus (h_-) helicities, represented by $\mu_+(H)$ and $\mu_-(H)$, respectively. A multilayer film, Ta(1)/Ru(1)/$Co_{70}Fe_{30}$(4)/$Mn_{75}Ir_{25}$(10)/Ru(30)/Ta(10)/SiO_2/Si(substrate), was used as the sample in the present study. The numbers in parentheses represent the thickness of each layer in nanometers.

Figure 2(a) shows the absorption and XMCD spectra for the Co $L_{2,3}$-edges. The spectra were recorded under a static magnetic field of 1.9 T by the conventional helicity switching technique in 1 Hz. The photon energy of 780 eV, at which the XMCD effect reaches a maximum, was chosen for the element-specific magnetization measurements using the pulse magnet. Figure 2(b) shows the results of high-magnetic-field XMCD measurement. The time dependence of the variations in absorption for h_+ and h_- have opposite signs, and successfully yields the XMCD profile. The magnetic field dependence of the XMCD intensity, $\mu_m(H)$, is shown in the inset of Fig. 2(b) and gives an identical magnetization curve to that measured with a SQUID magnetometer (not shown). The inset of Fig. 2(b) also confirms that the accuracy improves by using the appropriate statistical processing, which takes the average XMCD intensity for every 0.25 T of magnetic field and gives a reliability of about ±1% with respect to the saturated XMCD value. In order to confirm the fact that photon energy

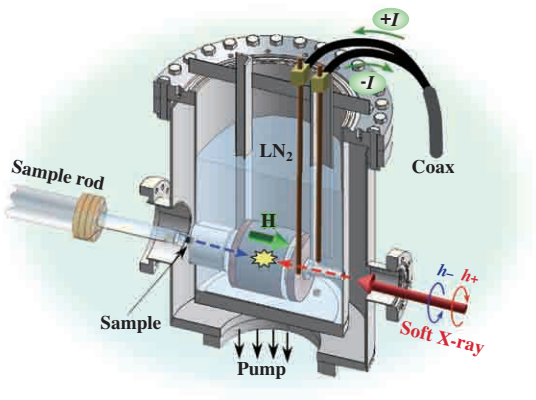

Fig. 1. Schematic drawing of the ultra-high vacuum (UHV) chamber equipped with a nondestructive pulse magnet. The magnet is directly cooled by liquid nitrogen.

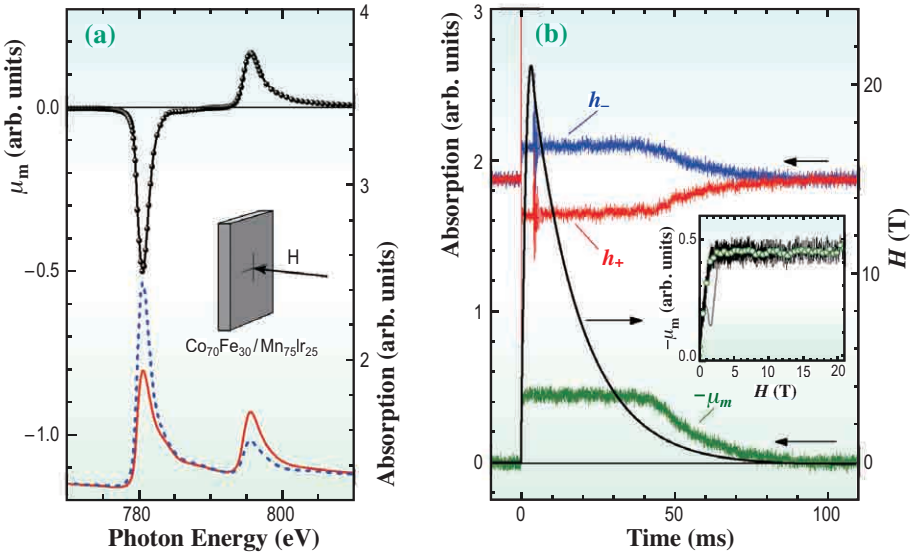

Fig. 2. **(a)** Absorption and XMCD spectra at Co $L_{2,3}$-edges of Ta/Ru/$Co_{70}Fe_{30}$/$Mn_{75}Ir_{25}$/Ru/Ta/SiO_2/Si(substrate) film. **(b)** Main window: time dependence of magnetic field, absorptions for plus (h_+) and minus (h_-) helicities at 780 eV, and XMCD (μ_m) given as the difference between the two absorption profiles. [1]

dependence of $\mu_m(H)$ profiles gives magnetic field dependence of XMCD spectra, the $\mu_m(H)$ profiles were measured at 41 photon energy points. Figure 3 shows the result of the measurement with a magnetic field of up to 6 T and confirms that the XMCD spectrum can be obtained by projecting μ_m (H) profiles onto the photon energy axis.

In the present study, we successfully developed the high-magnetic-field XMCD technique using the pulse magnet, which greatly exceeded the previous maximum field of 10 T. The maximum magnetic field of 30 T has already been used for soft XMCD studies, and a project for generating a field of 40 T is going to be operational by summer 2012.

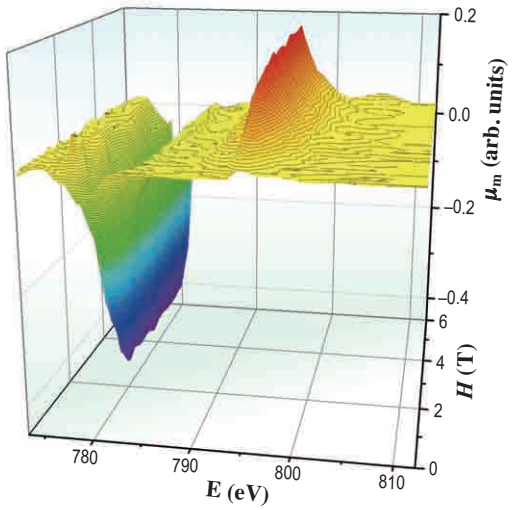

Fig. 3. Three-dimensional display of the energy dependence of high-magnetic-field XMCD profiles up to 6 T. [1]

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Reference

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