Direct Observation of Step-induced Magnetic Domain Formation in Manganite Films

There has been a great deal of interest recently in a spin tunnel junction employing half-metallic ferromagnets as electrodes because of their potential applications to future spintronic devices. The half-metallic ferromagnetic oxide $La_{0.6}Sr_{0.4}MnO_3$ (LSMO) is one of the most promising materials for spintronic devices owing to full spin polarization of its conduction carriers and high Curie temperature of 350 K [1]. However, in spite of intensive studies, a high performance device has not been realized. To improve the performance of an LSMO-based spintronic device, it is indispensable to obtain the information on the magnetic anisotropy and domain structure of LSMO films.

Photoelectron emission microscopy (PEEM) combined with X-ray magnetic circular dichroism (XMCD) is a powerful technique for studying this issue. Since XMCD provides information on the magnetization vector projected in the incident direction of a synchrotron radiation (SR) beam, it is possible to obtain all the three independent components of the magnetization vector by rotating the sample. The mapping of the magnetization distribution with a high spatial resolution enables us to observe the magnetic domain structures in ferromagnteic materials (Fig. 1). To determine the complex magnetic domain structure of LSMO films, we have performed the direct XMCD-PEEM observation of the in-plane magnetic domain structure of LSMO films epitaxially grown on stepped $SrTiO_3$ (STO) substrates [2]. XMCD-PEEM experiments were carried out using Elmitec PEEMSPECTOR at the soft-X-ray undulator beamline **BL25SU** [3].

Figures 2(a) and 2(b) show the magnetic domain images of LSMO films obtained at the azimuthal angles of 0° and 90° between the incident SR beam direction and the [100] direction, respectively. The bright and dark parts in the images correspond to magnetic domains with magnetization vectors parallel and antiparallel to the incident SR beam, respectively. The elongated magnetic domains along the [100] direction can be clearly observed in Fig. 2(a), where the incident SR beam is parallel to the [100] direction. The existence of "stripe" domains is clearly indicative of the uniaxial magnetic anisotropy of LSMO thin films. The uniaxial magnetic anisotropy may be induced by the step structure along the [100] direction on the surface of LSMO films (see the inset in Fig. 2(a)),

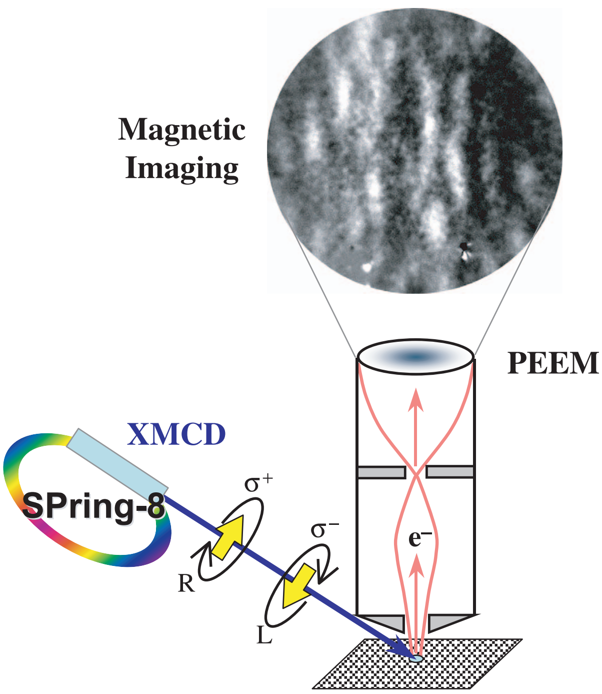

Fig. 1. Schematic illustration of XMCD-PEEM observation.

since the [100] and [010] directions are crystallographically equivalent in the case of LSMO films grown on STO substrates.

The uniaxial nature was further confirmed by measuring the azimuthal angle dependence of domain contrast in XMCD-PEEM images. As expected, the contrast between the stripe domains disappears completely when the direction of the SR beam is perpendicular to the step direction, as shown in Fig. 2(b). Instead, we can see a weak bubble-like contrast in Fig. 2(b), which suggests the existence of additional magnetization components perpendicular to the step direction. Such magnetic domain formation strongly suggests the presence of an additional magnetic anisotropy, namely, a biaxial magneto-crystalline anisotropy, with the easy axis along the [110] direction in LSMO films grown on STO substrates [4].

The direct observation of the magnetic domain structure by XMCD-PEEM suggests that the competition between two magnetic anisotropies, namely, the step-induced uniaxial magnetic and biaxial magnetocrystalline anisotropies, plays an important role in defining the magnetic properties of LSMO films and also provides the possibility of controlling the magnetic domain structure of LSMO films by the competition between the two magnetic anisotropies with different symmetries. Moreover, the present study demonstrates the usefulness and reliability of XMCD-PEEM for studying the magnetic anisotropy and domain structure of magnetic materials. We hope that this study promotes further XMCD-PEEM works on various types of magnetic materials for spintronic devices at SPring-8 in the near future.

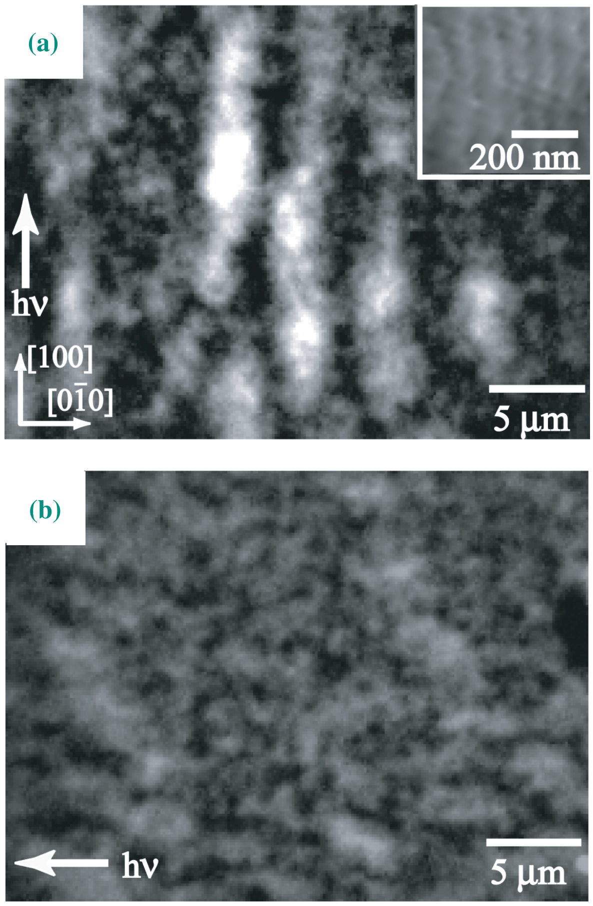

Fig. 2. Magnetic images of ferromagnetic LSMO film obtained at photon energy corresponding to Mn L_3-edge. The incident direction of the synchrotron radiation beam was parallel to the **(a)** [100] and **(b)** [010] directions. The atomic step direction is aligned with the [100] direction, as shown in the atomic force microscopic image in the inset.

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