Lorentz transmission electron microscopy study on a magnetoelectric Z-type hexaferrite

M. Okabe[1], T. Asaka[1], K. Fukuda[1], S. Hirose[2], K. Haruki[3], K. Okumura[3], and T. Kimura[3]

[1]Department of Materials Science and Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan
[2]Murata Manufacturing Co., Ltd., Nagaokakyo, 617-8555, Japan
[3]Division of Materials Physics, Graduate School of Engineering Science, Osaka University, Toyonaka, 560-8531, Japan

The magnetoelectric (ME) effect observed in some spiral magnets [1] is of great interest because it is attributed to the strong coupling between ferroelectricity and magnetic order. Such coupling enables to control magnetization or electric properties by the application of magnetic and/or electric fields. Here, typical ME materials exhibit the effect under relatively high magnetic field (> 1 T) and at low temperatures (< 150 K). This is an issue for an application for devices. Recently, however, ME effects at room temperature have been discovered in a Z-type hexaferrite $Sr_3Co_2Fe_{24}O_{41}$ even by applying a low magnetic field [2]. For applications, it is important to understand the interactions among magnetic ordered, (ferro) electric and crystallographic domains in the ME materials in real space. We investigated the magnetic domain structures in $(Ba,Sr)_3Sr_2Fe_{24}O_{41}$ by Lorentz transmission electron microscopy (LTEM).

For the LTEM observation, the polycrystalline samples were thinned by mechanical grinding and an Ar^+ ion sputtering. The specimens were examined using a Lorentz electron microscope, Hitachi HF-3000L, which is equipped with a custom-made field-free objective lens. We used the conventional Fresnel method for magnetic domain imaging, and analyzed the Fresnel images using the commercial software QPT FOR DIGITALMICROGRAPH [3] which enabled us to quantitatively measure the phase changes of electron waves and the local magnetization in the sample, based on the transport-of-intensity equation (TIE) [4–6].

Figure 1 shows the magnetization-distribution map derived from TIE. Local magnetization directions found to be oriented perpendicular to the crystallographic *c* axis. Consequently the magnetic domains are formed in a 180-degree domain structure. Here, in LTEM, magnetic components only on a plane normal to the electron optical axis are imaged. Then, Fig. 1(b) suggests that the magnetic domain walls are Bloch-type one, where the in-plane components are obviously small. According to Soda *et al.*[7], $Sr_3Co_2Fe_{24}O_{41}$ has the transverse conical magnetic structure at room temperature, as shown in Fig. 2(a). The resultant magnetic moments are perpendicular to the *c* axis. The magnetic domain structure shown in Fig. 1 is consistent with such transverse conical magnetic structure. Furthermore, we consider that the observed magnetic domain walls have out-of-plane magnetic moments, i.e., Bloch-type wall, being along the conical cone axes in transient layers, as shown in Fig. 2(b).

References

[1] For example, T. Kimura et al., Phys. Rev. Lett. 94 (2005) 137201.

[2] Y. Kitagawa et al., Nature Mater. 9 (2010) 797.
[3] K. Ishizuka and B. Allman, J. Electron Microsc. 54 (2005) 191.
[4] M. R. Teaque, J. Opt. Soc. Am. 73 (1983) 1434.
[5] K. A. Nugent et al., Phys. Rev. Lett. 77 (1996) 2961.
[6] V. V. Volkov and Y. Zhu, Phys. Rev. Lett. 91 (2003) 043904.
[7] M. Soda et al., Phys. Rev. Lett. 106 (2011) 087201.

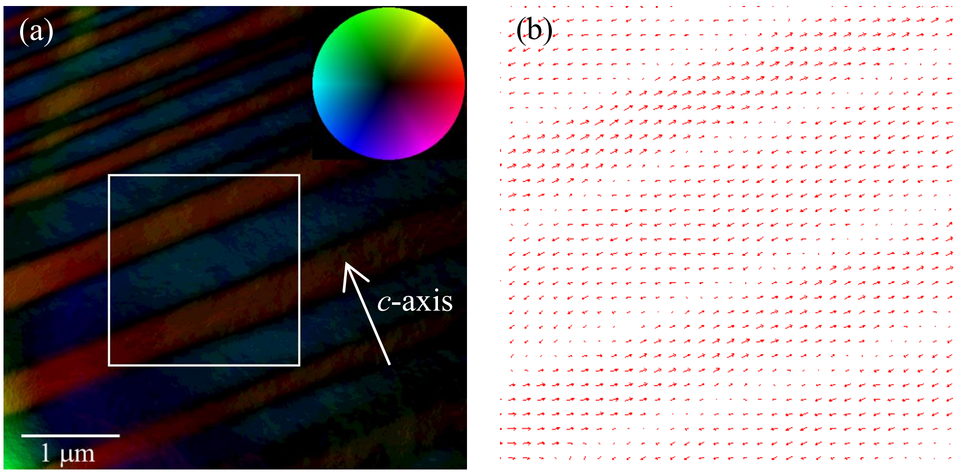

FIG. 1. (a) Magnetization-distribution map of $Sr_3Co_2Fe_{24}O_{41}$ derived by the transport-of-intensity equation (TIE) method. The inset is a color wheel for interpretation of the color distribution map. (b) Local magnetization distribution from TIE for the boxed region in (a).

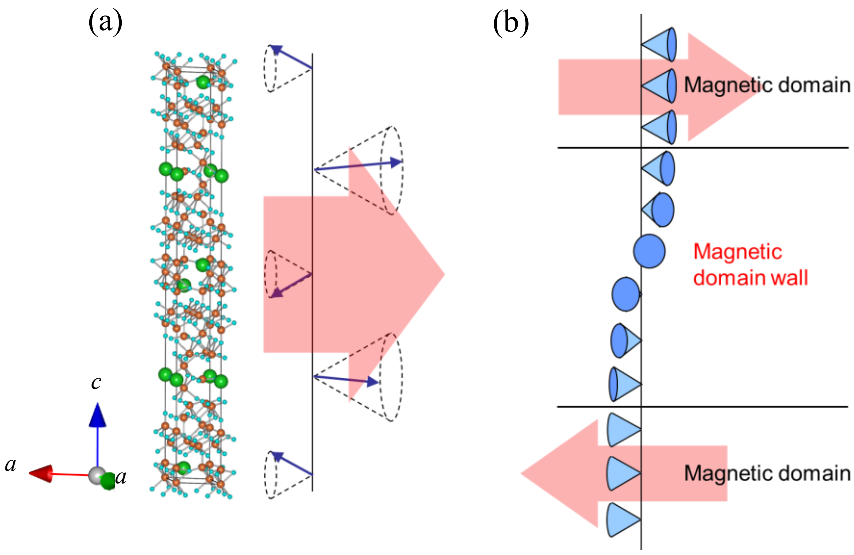

FIG. 2. (a) Crystal and magnetic structures of $Sr_3Co_2Fe_{24}O_{41}$. The small and large arrows represent the magnetic moments for the respective layers and the unit cell, respectively. (b) A possible model of the magnetic domain wall structure in $Sr_3Co_2Fe_{24}O_{41}$.