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Control of ferroelectric and ferromagnetic domains and realization of magnetization reversal by electric field in multiferroic $BiFe_{0.9}Co_{0.1}O_3$ thin films

Takuma Itoh

[Chapter 1] General Introduction

A multiferroic $BiFe_{0.9}Co_{0.1}O_3$ (BFCO), which is fabricated by partially substituting Fe in $BiFeO_3$ with Co, exhibits the coexistence of ferroelectricity and ferromagnetism along with their coupling and electric-field control of magnetism at room temperature. Owing to such attractive properties, BFCO is the most promising candidate for extremely low-energy consumption magnetic memory devices. This thesis clarified the changes in the ferroelectric and magnetic domains using several electric-field-applied methods and realized the deterministic control of the ferroelectric and ferromagnetic domains as well as the electric field-induced magnetization reversal.

[Chapter 2] Control of ferroelectric and ferromagnetic domains in $BiFe_{0.9}Co_{0.1}O_3$ thin films by utilizing trailing fields

An electric-field poling method of scanning the film surface with a voltage-applied cantilever was adopted for BFCO film/$SrRuO_3$ (bottom electrode)/$GdScO_3$ $(110)_o$ substrate ("o" denotes orthorhombic index). In this case, the vertical electric field between the cantilever and the bottom electrode and the in-plane "electric trailing field," caused by the distribution of the electric field from the biased cantilever, functioned simultaneously. Utilizing these two aforementioned electric fields, the polarization direction was deterministically controlled multiple times in both the out-of-plane and in-plane directions, while preserving the correlation between ferroelectric and ferromagnetic domains.

[Chapter 3] Out-of-plane polarization reversal and changes in in-plane ferroelectric and ferromagnetic domains of multiferroic $BiFe_{0.9}Co_{0.1}O_3$ thin films by water printing

The variations in the ferroelectric and magnetic domain structures after "water printing" were investigated, which is a technique for controlling the polarization of the ferroelectric thin films by chemical bonding and electrostatic energy accumulation at the solid–liquid interface. The out-of-plane 71° polarization switching, expected to induce a magnetization reversal, from the upward to downward direction was achieved in 88.4%

of the observed areas. The angle-resolved X-ray photoelectron spectroscopy (ARXPS) measurements revealed that the termination surface of BFCO was BiO, indicating that the positive-charge accumulation by H^+ binding to O in the BiO termination surface caused out-of-plane polarization reversal. The reversal of the out-of-plane component of magnetization occurred only in 50.1% of the corresponding region, signifying a loss of correlation between the ferroelectric and magnetic domains. The gradual polarization reversal by water printing with inhomogeneous nucleation of small ferroelectric domains may segment the magnetic domain into smaller variants and the magnetization reversal did not occur in half of the variants.

[Chapter 4] Magnetization reversal accompanying 109° polarization switching in multiferroic $BiFe_{0.9}Co_{0.1}O_3$ thin film

The results demonstrated the successful achievement of 109° polarization switching throughout the majority of the area after applying the in-plane $[1\bar{1}0]_{pc}$ electric field in $(110)_{pc}$-oriented BFCO thin film, which observed the reversal of the out-of-plane component of magnetization ("pc" denotes pseudocubic index). This is the first evidence of magnetization reversal in BFCO thin films accompanying 109° polarization switching.

[Chapter 5] General Conclusion

This research work demonstrated the electric-field control of magnetic domain at room temperature using several electric-field-application methods, electric-field poling by moving a biased cantilever, water printing, and in-plane electric field application with coplanar electrode. The present findings will aid in selecting the electric field application methods suitable for various experimental conditions to investigate the changes in the ferroelectric and ferromagnetic domains and the magnetization reversal accompanying polarization reversal in multiferroic materials.

In addition, the present results suggest the applicability of BFCO for ultralow-consumption electric-field-write and nonvolatile magnetic-read-out memory device. Specifically, magnetization reversal accompanying both in-plane and out-of-plane polarization reversal were demonstrated, which increased the applicability of the multiferroic device.