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題目(和文)	マルチフェロイックBiFe0.9Co0.1O3薄膜における強誘電性・強磁性ドメイン制御と電場印加磁化反転の実現
Title(English)	Control of ferroelectric and ferromagnetic domains and realization of magnetization reversal by electric field in multiferroic BiFe0.9Co0.1O3 thin films
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種別(和文)	論文要旨
Type(English)	Summary

（博士課程）
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論 文 要 旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	材料 系 材料 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of （ 理学 ）
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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Multiferroic materials exhibit various ferroic orderings and attractive physical phenomena, offering potential technological applications that are superior to those of conventional materials. In particular, the coupling of ferroelectricity and magnetism along with the manipulation of magnetic ordering by the electric field has garnered scholarly interest. The latter phenomenon can be utilized for innovative devices such as electric field-control magnetic memories that avoid the energy-consuming writing process of typical magnetic memories. Co-substituted $BiFeO_3$ is a highly promising multiferroic material that exhibits robust ferroelectricity coexisting with weak ferromagnetism, and their coupling and electric-field control of magnetism have been confirmed at room temperature. This study explored the device application of this compound by studying the changes in the ferroelectric and magnetic domains and attempted to control the electric polarization and spontaneous magnetization directions by electric field in Co-substituted $BiFeO_3$ thin films.

In Chapter 2, the surface of a multiferroic $BiFe_{0.9}Co_{0.1}O_3$ (BFCO) thin film was scanned with a voltage-applied cantilever to apply an electric field to the film and attempted to arbitrarily control the ferroelectric and magnetic domains utilizing the vertical electric field between the cantilever and the bottom electrode and the in-plane effective electric field termed as the “trailing field.” There are two types of trailing fields: electric trailing field caused by the distribution of the electric field from the cantilever, and the flexoelectric trailing field caused by mechanical strain. Observably, the electric trailing field was dominant in the current experimental conditions. Overall, the direction of the electric polarization could be controlled in an arbitrary direction utilizing the electric trailing field. As the magnetic domain structure was similar to the ferroelectric domain structure, the magnetic domain could be controlled by the electric trailing field preserving the correlation between the electric polarization and magnetization. The estimated magnitude of the electric trailing field required the polarization reversal of an order of magnitude smaller than that required for the in-plane coplanar electrode. The above-mentioned results suggested that the electric trailing field is a valuable tool for manipulating both the ferroelectric and magnetic domains in multiferroic BFCO thin films.

In the subsequent chapter, "water printing," a technique for controlling the polarization of ferroelectric thin films by chemical bonding and electrostatic energy accumulation at the solid–liquid interface, was applied on BFCO/$SrRuO_3$ (bottom electrode)/orthorhombic (110)-oriented $GdScO_3$ substrate. Water printing with pure water (pH = 6.2) reversed the out-of-plane component of the polarization of BFCO from upward to downward owing to the positive charge accumulation by H^+ binding to O in the BiO termination surface of the BFCO. The shape of all the in-plane ferroelectric domains before and after water printing remained unchanged. This result indicated that the out-of-plane 71° polarization switching, which could induce a magnetization reversal, was achieved across the entire film. The quantitative analysis of ferroelectric and ferromagnetic domains revealed the achievement of 71° switching in 88.4% of the observation area. However, the reversal of the OOP component of magnetization occurred only in 50.1% of the corresponding region, indicating a loss of the 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.

Although magnetization reversal accompanying 71° out-of-plane polarization switching has been observed, it remained a question whether the magnetization can be reversed in 109° switching. In Chapter 4, an in-plane electric field was applied in the $[1\bar{1}0]$ direction of (110)-oriented BFCO thin films in the pseudocubic notation, corresponding to the direction of 109° polarization switching, with the Pt in-plane coplanar electrode on top of the film and the ferroelectric and magnetic domains were observed before and after polarization reversal. The uniform electric field generated by the 100-μm-wide coplanar electrode and a gap distance of 1 μm enabled the reversal of the $[1\bar{1}0]$ component of electric polarization, i.e., 109° polarization switching. Moreover, the magnetization reversal occurred in the region with 109° in-plane polarization switching. This is the first demonstration of the magnetization reversal accompanying 109° polarization switching, which will further accelerate the memory applications of BFCO.

This study clarified the changes in the ferroelectric and magnetic domains under the application of several electric fields. The deterministic control of the ferroelectric and ferromagnetic domains and the electric field-induced magnetization reversal were successfully achieved. The magnetization reversals were observed to accompany both out-of-plane (71°) and in-plane

(109°) polarization switchings. These results suggest the applicability of BFCO for ultralow-consumption electric-field-write and nonvolatile magnetic-read-out memory device, which further expand the possibility of BFCO-based device application.