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Investigation of Dzyaloshinskii-Moriya Interaction in Rhombohedral and Tetragonal $BiFeO_3$/CoFe Bilayers

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1. Introduction

Multiferroic $BiFeO_3$ (BFO) is attractive material because ferroelectricity and antiferromagnetism coexist above room temperature (RT). In the BFO/ferromagnets bilayers, electric polarization switching can change the magnetization direction in ferromagnetic layer through exchange bias (EB) effect at the interface between BFO/ferromagnet bilayers. This mechanism is useful for voltage operated magnetic random access memory (V-MRMA) for non-volatile memory with low power consumption. Some studies have already demonstrated the electrical manipulation of the magnetization direction in ferromagnetic layer for BFO/ferromagnets bilayers [1-3]. In this mechanism, EB between BFO and ferromagnetic layer is very important. However, there are a few reports on EB for BFO/ferromagnets bilayers [4-6] and the understanding of EB is not enough. For earlier realization of V-MRAM, investigation of EB for more understanding is necessary. Then, we focused on that the crystal symmetry of BFO epitaxial films changed among rhombohedral(*R*), tetragonal(*T*) and monoclinic(*M*) structure owing to sputtering gas, power, and substrate temperature on the $SrTiO_3$(STO) substrates [7, 8]. EB observed ever was mostly using *R*-BFO/ferromagnets bilayers because EB operation is based on Dzyaloshinskii-Moriya (DM) interaction in rhombohedral crystal symmetry [9]. Therefore, there are no reports on EB for *T*- and *M*-BFO/forromagnets bilayers, and it has never been clarified that the relationships between the crystal symmetry of BFO and EB for BFO/ferromagnets bilayers, and the role of DM interaction in exchange bias system is not clear.

In this study, we prepared *R*- and *T*-BFO/CoFe bilayers and investigated the EB properties.

2. Experiments

The BFO films (80 nm) were deposited on STO (100) substrates with substrate temperature (T_s) 600°C by r.f. magnetron sputtering. To modify the crystal symmetry of BFO, partial oxygen gas pressure (P_{O2}) during the sputtering was changed from 0 to 36 mPa. Then, CoFe was deposited 4.0 nm on BFO with applying 150 Oe external magnetic field ($H_{dep.}$) with T_s = RT. Film structure was evaluated by θ-2θ , ω, φ scan and x-ray reciprocal space mapping (XRSM). The EB properties of BFO/CoFe bilayers were evaluated by VSM and SQUID.

3. Results and Discussions

Figure 1 shows θ-2θ profiles of BFO films with various P_{O2} (mPa). For the BFO films with P_{O2} = 0 mPa, secondary phase such as Bi_2O_3 was appeared. When P_{O2} was 18 and 36 mPa, single phase of BFO was formed. In addition, the crystallinity was found to become lower with increasing P_{O2} by ω scan, and epitaxial growth for each P_{O2} was confirmed by φ-scan measurement (not shown).

Figure 2 shows XRSM images for the P_{O2} = 0, 18, and 36 mPa. For P_{O2} = 0 mPa, the (202) diffraction was confirmed as single spot. On the other hand, two split peaks of BFO (202) were observed for P_{O2} = 18 and 36 mPa. According to *K. Saito et al* report [10], these (202) peak splits indicate that the BFO film with P_{O2} = 0 mPa has *T* (*c*/*a* = 1.05), and films with P_{O2} = 18 and 36 mPa have *R* symmetry.

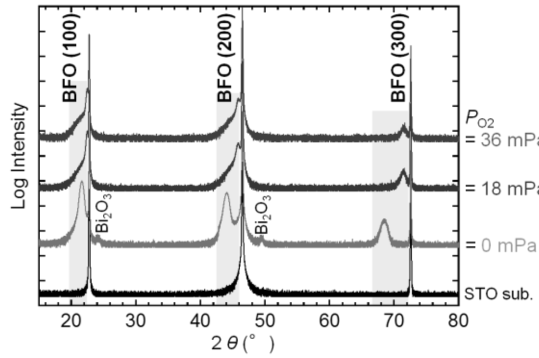

Fig. 1 *θ-2θ* profiles of BFO single layers.

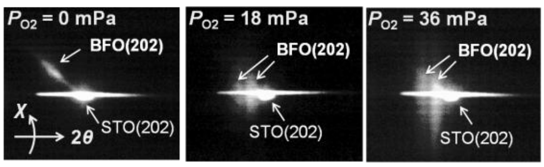

Fig. 2 XRSM images of BFO single layers.

In above experiments, it was found that BFO epitaxial films with *T*-symmetry were successfully obtained at P_{O2} = 0 mPa and *R*-symmetry at P_{O2} = 18 , 36mPa respectively. So, in the following, we fabricated *T*- and *R*-BFO/CoFe bilayers and investigated EB properties.

Figure 3 shows the magnetization curves for the BFO/CoFe bilayers measured by VSM at 300 K. Magnetic field (*H*) was applied to the same direction as H_{dep}. For the *R*-BFO/CoFe bilayers, the magnetization curves shifted by 50 Oe (b: P_{O2} = 18 mPa) and 20 Oe (c: P_{O2} = 36 mPa) to negative field. On the contrary, for the *T*-BFO/CoFe bilayer showed increase of coercive field; however, the shift of the magnetization curve was not observed (c: P_{O2} = 0 mPa).

Figure 4 shows the applied magnetic field angle (θ_H) dependence of magnitude of magnetization curve's shift from zero field (H_{ex}) and coercive field (H_c). We defined the applied field direction when CoFe layers were depositted as θ_H = 0°. For *R*-BFO (P_{O2} = 18, 36 mPa)/CoFe bilayers, unidirectional anisotropy was observed, which clearly indicates that the EB resulted from DM interaction occurs at the interface between *R*-BFO/CoFe bilayers. On the contrary, for *T*-BFO (P_{O2} = 0 mPa)/CoFe bilayer, θ_H dependence of H_{ex} is quite different from those of *R*-BFO/CoFe bilayers and it seems that unidirectional anisotropy due to EB was not observed, which was suggested that DM interaction disappeared at the interface between *T*-BFO/CoFe bilayers.

For more investigation for *T*-BFO/CoFe bilayer, the temperature dependence of H_{ex} and H_c for *T*-BFO/CoFe bilayer was measured by SQUID. In addition, CoFe directly deposited on STO substrate was also measured for comparison. In this measurement, magnetic field was applied to the angle at θ_H = 0°. As shown in figure 5, H_c increased with decreasing temperature for *T*-BFO/CoFe bilayer in comparison with STO/CoFe, which indicates the increase of H_c is contribution from *T*-BFO. In addition, H_{ex} was observed and increased monotonically bellow 200 K.

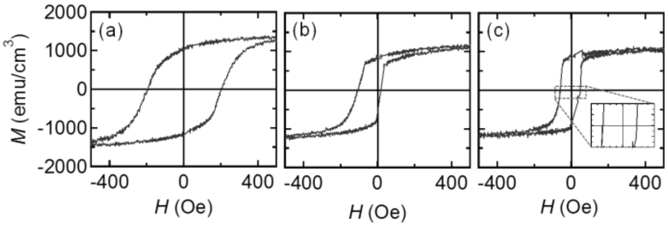

Fig. 3 Magnetization curves of (a)*T*- and (b),(c) *R*-BFO/CoFe bilayers measured at 300 K

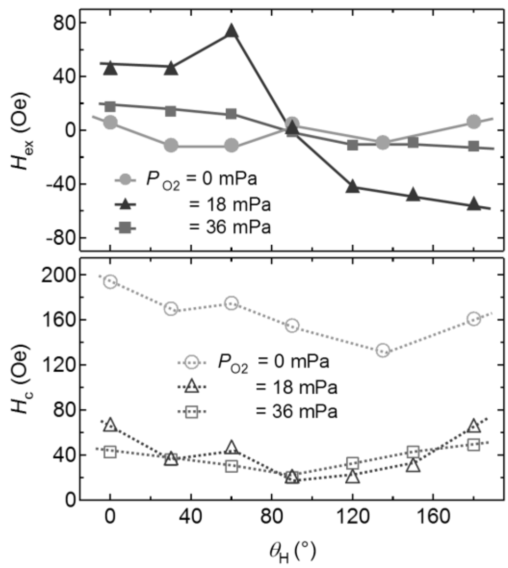

Fig. 4 Applied magnetic field angle dependence of H_{ex} and H_c for BFO/CoFe bilayers.

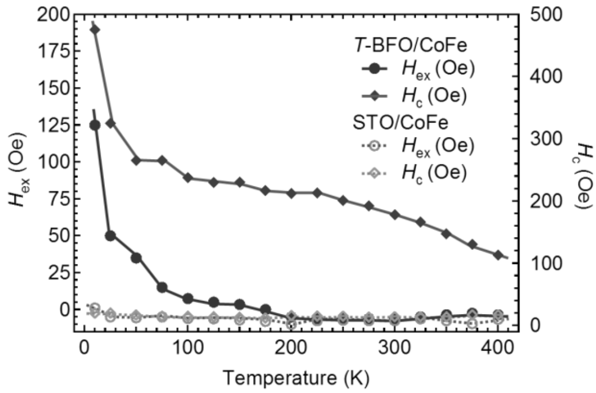

Fig. 5 Temperature dependence of H_{ex} and H_c for *T*-BFO/CoFe bilayer

4. Summary

R- and *T*-BFO/CoFe bilayers were prepared, and the EB effect of them was investigated. The EB induced by DM interaction was clearly observed for the *R*-BFO/CoFe bilayers at 300K. For *T*-BFO/CoFe bilayer, on the other hand, EB was observed at only low temperature bellow 200 K and it was revealed that the DM interaction may disappear at 300K.

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