Magneto-Electric Resistance Modulation of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ Ferromagnetic Thin Film*

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We have demonstrated electric field-induced resistance change in a Cr_2O_3 /ultra-thin $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) magnetic heterostructure. By the application of an electric field to the Cr_2O_3 gate, the resistance of the LSMO film was changed. The temperature dependence of the resistance change has a maximum around 220 K. Since the temperature dependence of the magneto-electric (ME) susceptibility of Cr_2O_3 has the same tendency, this resistance change is more likely due to the ME effect of the Cr_2O_3 film. [DOI: 10.1380/ejssnt.2010.318]

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I. INTRODUCTION

The phenomenon of colossal magneto-resistance in manganite perovskite materials has attracted attention with regard to the potential use of these materials in new spintronics devices. The resistance change in these materials is in the range of approximately 1000%, which is larger than those of general magnetoresistance effects. On the other hand, magneto-electric (ME) effects have also received attention because the magnetic or dielectric properties can be controlled by an external electric or magnetic field [1, 2]. In the present study, we focused on Cr_2O_3 , which shows the antiferromagnetic properties of ME materials [3, 4]. If we create a magnetic heterostructure using Cr_2O_3 , we can control its magnetic configuration through exchange coupling to adjacent ferromagnetic films by using the ME effect without an external magnetic field [5]. We have previously reported an exchange interaction in a Cr_2O_3 /LSMO (AF/FM) heterostructure [6]. In the present paper, we demonstrate magneto-electrical resistance modulation of a ferromagnetic $(\text{La}_{0.7}\text{Sr}_{0.3})\text{MnO}_3$ (LSMO) film beneath the Cr_2O_3 film using the mechanism described above.

II. EXPERIMENTAL

The Cr_2O_3 /LSMO heterostructure was prepared using radio-frequency (RF) magnetron sputtering. Cr_2O_3 and stoichiometric LSMO sintered ceramics were used as the target, and SrTiO_3 was used as the substrate. The substrate was annealed at 1000°C for 3 hours in an oxygen atmosphere to obtain a step and terrace structure. The base pressure before introducing the sputtering gas was 3.0×10^{-4} Pa, and the gas pressure during deposition was 8.0×10^{-1} Pa. The gas used was a mixture of Ar and O_2 , and the Ar/ O_2 ratios for LSMO were 9:1. LSMO film with a thickness of 200 nm was deposited at 400°C. The as-deposited LSMO did not show ferromagnetic properties, due to the low growth temperatures, and therefore

the samples were annealed at 900°C for 10 h in air. Cr_2O_3 with a thickness of 200 nm was deposited at 400°C. The gas used was a mixture of Ar and O_2 , with a ratio for Cr_2O_3 of 16:1. Pt was used as a top gate electrode with a size of 500 μm . Au was used as the source-drain electrode, with a drain-source length of 500 μm . The magnetic properties of the sample were measured using a Superconducting Quantum Interface Device (SQUID). A magnetic field of 500 Oe was used as the measurement field applied parallel to the surface of the film, corresponding to the saturation magnetic field of the LSMO. In order to investigate the interface magnetic properties, M-T measurements after field cooling (FC) with a magnetic field of 0.5 T were also performed. Structural analysis of the films was carried out with an X-ray diffractometer (XRD) using Cu K α radiation and Reflection High Energy Electron Diffraction (RHEED). The surface morphology was measured using an Atomic Force Microscope (AFM). The electrical properties at low temperature were measured using a cryostat system (Nagase PS25SR). The effect of the electric field on source-drain resistance of LSMO was evaluated by applying an electric field to the Cr_2O_3 gate. The electric field-induced resistance change (ER) was defined as $\text{ER} = (R_E - R_0) \times 100 / R_0$, where R_0 and R_E are the drain-source resistance at zero field and at a certain field, respectively.

III. RESULTS AND DISCUSSIONS

Figure 1(a) shows the X-ray diffraction pattern of the sample. Figures 1(b) and (c) show an AFM image and the surface profile along the dotted line in the AFM image, respectively. The diffraction peaks were identified as SrTiO_3 ($K\alpha_1$ and $K\alpha_2$), LSMO and Cr_2O_3 . We have previously reported an LSMO film that was epitaxially grown on a SrTiO_3 substrate using the same deposition conditions [6]. We also revealed the epitaxial nature of the sample before depositing the Cr_2O_3 film, using RHEED analysis. The Cr_2O_3 film has a 006-oriented polycrystalline structure. The RMS roughness of 5 nm indicated that the sample was sufficiently smooth to apply a uniform voltage on the Cr_2O_3 gate.

Figure 2 shows the magnetization curves (M-H) measured at 100 K. In order to create a pinning state of the ferromagnetic domain by an exchange bias, this measurement was performed with an FC field of 0.8 T. A hysteresis shift in the M-H curve was observed upon applying the FC field. The exchange bias field was approximately

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FIG. 1: XRD pattern of the Cr_2O_3 film deposited on LSMO. Figures (b) and (c) show an AFM image of the Cr_2O_3 film and the surface profile along the dotted line in the AFM image, respectively.

FIG. 2: M-H curves of the samples without/with field cooling. The FC field was 0.8 T.

2 mT for the FC field of 0.8 T. The sign of the exchange bias field was determined by the competition between the antiferromagnetic exchange coupling of the pinning and the LSMO magnetization, with the Zeeman interaction energy of the pinning system [7]. For our system, a positive exchange bias was observed. This means that the Zeeman interaction overcomes the antiferromagnetic exchange coupling that aligns the pinning moments parallel to the external magnetic field in our sample. When the electric field is applied to the Cr_2O_3 gate, the interaction between the induced magnetic moment and the LSMO moment is also dominated by the Zeeman interaction.

Electric field-induced resistance changes (ER) with/without FC were investigated at various temperatures. First, we made sure that the leakage current of the Cr_2O_3 gate did not affect the current in the LSMO channel. The leakage current was less than approximately 1×10^{-7} A, and the change in the range of resistance was approximately 1×10^{-4} A. As such, the leakage current for Cr_2O_3 can be considered to be negligible. These results are shown in Figs. 3(a) and (b). The ZFC-ER of the sample gradually decreased with increasing external electric field at every measurement temperature. The value of ZFC-ER increased with an increase in the measurement temperature. The

FIG. 3: Electric field-induced resistance changes (ER) of the sample with ZFC and FC measured from 100 K to 180 K.

FIG. 4: Temperature dependence of the absolute values of ZFC/FC-ER on the electric field of 5.0 kV/cm.

FC-ER had same tendency as the ZFC-ER. The FC-ER has same tendency as the ZFC-ER. LSMO is p-type carrier mediated ferromagnetic semiconductor. When the positive electric field is applying on the Cr_2O_3 gate, a depletion layer is formed in Cr_2O_3 /LSMO interface. Although the magnetic order should become weak, our result is opposite. These behaviors could be explained by the ME effects in the Cr_2O_3 film. First, the ZFC sample has a random magnetic domain state. In response to the application of an electric field, the induced magnetic moment originating from the ME effects can align the magnetic domain because the induced moment

positively affects the LSMO, as mentioned in the section on magnetic properties, which in turn is similar to the effect of applying the magnetic field. Therefore, the ZFC resistance increased due to the magnetic domain alignment process at a low electric field. The FC-ER behavior could also be similarly explained. A different FC field resulted in a different order of the magnetic domain [8]. The induced magnetic moment by the ME effects could enhance the order state of the magnetic domain. Estimates by Hochstrat *et al.* [9] have indicated that the expected ME field is approximately 1 mT in response to the application of an electric field of 5.0 kV/cm. This is sufficiently high to realign the magnetic domain from the FC state to another magnetic domain state. In order to investigate details of the difference between the ZFC-ER and FC-ER, the temperature dependence of the absolute values of ZFC/FC-ER on the electric field of 5.0 kV/cm was re-plotted using Fig. 3, as shown in Fig. 4. Both ER values had a maximum around 220 K. This result supports the assumption that the ME effect plays an important role for ER behavior, since the ME susceptibility is largest at approximately 220 K [4]. Kita *et al.* have reported that the maximum ME susceptibility is caused by an ME effect easy axis change from the c-axis (at high temperature) to the a-axis (at low temperature). Since our sample has a 006 preferentially oriented Cr₂O₃ gate, magnetic domain alignment caused by the ME effect should be large above 220 K. Therefore, the ER values of FC-ER are larger than those of ZFC-ER above 220 K. On the other hand, the reason why there are no differences in the ER values between ZFC and FC below 200 K is likely due to the ME axis change from

the c-axis to the a-axis. Though we have demonstrated this behavior from 100 K to 240 K, which is a low temperature range for commercial devices, this behavior can be useful for magnetic domain reverse process control by an electric field in magnetic hetero-devices, such as magnetic random access memory and magneto tunneling junctions.

IV. CONCLUSIONS

We have demonstrated electric field-induced resistance changes in a Cr₂O₃/LSMO magnetic hetero system. The sample showed a positive shift in its magnetization curve when subjected to an FC field. By application of an external electric field to the Cr₂O₃ gate, the resistance of the LSMO was negatively changed. The ER ratio and differences in ER between the ZFC and FC revealed that this ER was more likely due to magnetic state tuning of the LSMO and exchange tuning between the Cr₂O₃/LSMO interface by the ME effects.

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