Insight into new magnetic recording principle with magnetoelectric writing

M. Sahashi, M. Al-Mahdawi, S. P. Pati, S. Ye, Y. Shiokawa, and T. Nozaki,
(Tohoku University)

The recording areal density has continued increasing to nearly 1Tbpsi with Perpendicular Magnetic Recording (PMR). However, it seems that the growth rate of a recording areal density is fairly reduced for the trilemma problem due to particulate magnetic recording principle. Of course, such alternative technologies or methods as energy assisted recording (HAMR, MAMR etc.) have been worked on with energy towards realizing the next generation recording system where they are still based on a particulate magnetic recording principle. Considering a magnetic recording (i.e. head/media system), STT and SOT are not suitable for magnetic recording principle. So in this paper we propose a new magnetic recording principle with voltage effect on magnetization-switching, especially Magnetoelectric Effect of Cr2O3 sesquioxide, that is to say that magnetic bits are written on Cr2O3 antiferromagnetic media by E(electric field)・H(magnetic field) product.

Magnetoelectric (ME) effect has so far been paid attention to be applied to a nonvolatile memory (NVM). Cr2O3 is a typical sesquioxide with ME effect and its antiferromagnetic Neel temperature is TN =307 K, which is higher than RT. A robust isothermal electric control of exchange-bias at RT is actually reported for bulk Cr2O3 single crystal sample when both of electric field E = 0.02 [MV/cm] and magnetic field H = -1.54 [kOe] was applied [1]. But ME effect has not yet been clarified in Cr2O3 thin films because of its large leakage current and imperfect antiferromagnetic-ordering while ME effect like behavior up to 200K is reported to be observed in an ultrathin Cr2O3/Fe2O3 Nano-Oxide Layer (NOL) [2]. When considering the application of ME effect to magnetic recording technology with voltage-controlled magnetization switching, there are some problems except the above issue, which should be resolved. The first is to realize and design an effectually high exchange-bias filed between antiferromagnetic (AFM) Cr2O3 and ferromagnetic (FM) thin film multilayers in the higher temperature range than RT, which means higher Neel temperature (TN) and higher blocking temperature (TB), where the properly low coercive force of FM is also required. The second is to invest FM layer with a perpendicular anisotropy which is thought to be caused by both of the hybridization of FM 3d and O 2p orbitals and the magnetic coupling at the interface between FM and Cr2O3. The third is to confirm ME effect in the thin film Cr2O3 after getting Cr2O3 thin film which shows good electrical properties.

In this paper, electrical and magnetic performances of the thin film Cr2O3/Fe2O3 sesquioxide were investigated. We successfully fabricated the Cr2O3 and Fe2O3 thin films with small leakage current and good magnetic properties.
We successfully confirmed ME effect of Cr2O3 thin films (100nm~500nm) and the switching of both exchange bias field and residual magnetization using Co/Cr2O3 exchange bias bilayer with low FM layer coercivity (~20 Oe) structure, shown in Fig.2 under both of ME filed cooling and isothermal process conditions for the first time in the world [3],[4]. In addition, we succeeded in enhancing TM of Fe2O3 higher than 400K by Ir-doping where perpendicular-spin-alignment of Fe2O3 was also confirmed in both of Mossbauer spectroscopy and weak ferromagnetic moment measurement with SQUID magnetometer. These results support our new magnetic recording principle concept with voltage controlled magnetization switching of AFM Cr2O3 thin film above room temperature at the first step.
In addition, we also propose low EH product writing with positive exchange coupling in Chromia/Co bilayer system where an induced weak ferromagnetic moment is also observed of antiferromagnetic Chromia. The related experimental results and phenomenologically analytical consideration will be discussed.

This study was partially supported by ImPACT Program led by Council of Science, Technology and Innovation (CSTI), Cabinet Office of Government of Japan, and JST-ALCA Program.

References

[1] X. He, C. Binek et al., Nature Materials, 9 (2010) 579.
[2] N. Shimomura, T. Nozaki, and M. Sahashi et al, Appl. Phys. Lett. 101,012403 (2012)
[3] T. Ashida, T. Nozaki, M. Sahashi et al., Appl. Phys. Lett. 104, 152409 (2014).
[4] T. Ashida, T. Nozaki, M. Sahashi et al., Appl. Phys. Lett. 106, 132407(2015).

Characterization of magneto-electric switching energy in Cr_2O_3 antiferromagnetic thin films

M. Al-Mahdawi, S. P. Pati, S. Ye, Y. Shiokawa, T. Nozaki, and M. Sahashi
(Tohoku University)

Introduction: Towards applications in voltage-controlled HDD and MRAM, usually the ferromagnetic layer is considered as the "active" media. A possibility of using antiferromagnetic (AFM) media is hindered by the difficulty of controlling and accessing the antiferromagnetic state. Recently, there is a revival in utilizing the magnetoelectric (ME) antiferromagnet Cr_2O_3, where the electric control of perpendicular exchange-bias in a Cr_2O_3/Co multilayer system has been realized under the simultaneous application of electric and magnetic fields[1–4] . However, The required energy of the product of electric and magnetic fields (EH) is 2 to 3 orders of magnitude higher in thin-film systems compared with bulk crystals[1,5]. In this presentation, we will present the investigation of the origin of this increase, and a novel way to control it.

Experimental procedure: Two samples were used, sample A was a commercial bulk Cr_2O_3 substrate, sample B was a sputter-deposited thin-film sample of the following structure: *c*-Al_2O_3 sub./Pt 25 nm/Cr_2O_3 500 nm/Pt 25 nm. The average domain state of Cr_2O_3 was measured by the linear magnetoelectric susceptibility (α) in a SQUID magnetometer. The application of a small electric field (E) results in an induced magnetization (M = αE), and the sign of α indicates the AFM domain state of Cr_2O_3.

Results and discussions: Figure 1 shows the comparison between the temperature-dependence of α in samples A and B. Except for a small decrease in Neel temperature, the magnitude of α is same and the ME property is intrinsically similar in thin films as to bulk crystals. The increase of EH switching product in thin films is mostly due to the increase of exchange-bias energy density as the thickness becomes reduced orders of magnitude.

Additionally, we surprisingly found a weak magnetization from Cr_2O_3 films, which was coupled to AFM order parameter. This weak magnetization required an additional EH switching energy for single-layer Cr_2O_3. However, the sign of switching EH energy required to overcome the weak magnetization is opposite to the EH energy required to overcome the exchange-coupling energy with the Co layer. We could design a balance between both, and we could decrease the switching energy 2 orders of magnitude compared to other reports on thin-film Cr_2O_3.

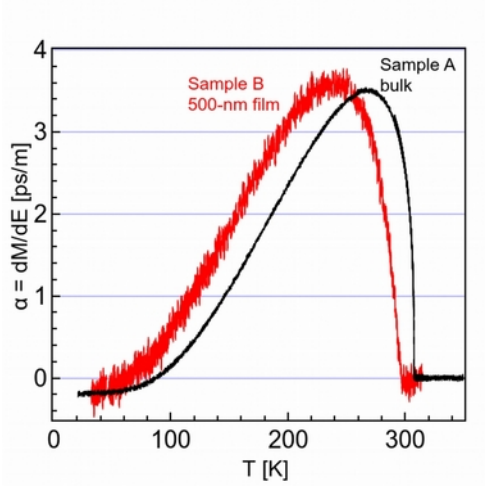

Fig. 1 Temperature-dependence of α in samples A and B

Acknowledgement: This work was partly funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Japan Government).

References

1) T. Ashida *et al.,* Appl. Phys. Lett. **104** (2014) 152409.
2) K. Toyoki *et al.,* J. Appl. Phys. **117,** (2015) 17D902.
3) T. Ashida *et al.,* Appl. Phys. Lett. **106,** (2015) 132407.
4) K. Toyoki *et al.*, Appl. Phys. Lett. **106,** (2015) 162404.
5) P. Borisov *et al.,* Phys. Rev. Lett. **94,** (2005) 117203.

Magnetic field dependence of threshold electric field for switching exchange bias polarity

T. V. A. Nguyen, Y. Shiratsuchi, R. Nakatani
Department of Materials Science and Engineering, Graduate School of Engineering, Osaka University

Electric field control of magnetization in magnetoelectric (ME) insulators plays an important role in spintronic applications owing to various advantages such as the high processing speed and the low power consumption. Antiferromagnetic (AFM) α-Cr_2O_3 is a typical ME material which showed a fascinating exchange bias as coupled with a ferromagnetic layer [1, 2]. The isothermal ME switching of the perpendicular exchange bias in an all-thin-film system was reversibly achieved with the change in polarity of exchange bias from negative-to-positive (N-to-P) and positive-to-negative (P-to-N) by tuning the applied electric field while maintaining the magnetic field [1]. At a temperature, the threshold electric field (E_{th}) at which the polarity of exchange bias is reversed depends on the applied magnetic field [1]. However the study on magnetic field dependence of E_{th} for switching exchange bias polarity, which is indispensable for future spintronic devices, is still insufficient.

In this study, we investigated the isothermal ME switching of perpendicular exchange bias in Cr_2O_3. Pt/Co/spacer/Cr_2O_3/Pt stacked films were prepared on an α-Al_2O_3 substrate using DC magnetron sputtering system. The isothermal switching of exchange bias was investigated by the anomalous Hall effect (AHE) measurement using a Hall-bar device with a 2-μm-width and a 40-μm-length. At 275 K, the exchange bias field was reversibly switched by reversing the electric field under a fixed magnetic field. Fig. 1 shows the hysteretic electric field dependence of the exchange bias field (left) and remanence ratio (right) under -60 kOe at 275 K. The rectangular hysteresis is in agreement with the isothermal switching of AFM domain state in Cr_2O_3. Fig. 2 shows the magnetic field dependence of E_{th} for switching exchange bias polarity, in which E_{th} was evaluated from the cross point of remanence ratio curve with the horizontal axis for both N-to-P and P-to-N processes. The switching condition, simply expressed by EH_{th} = constant, followed the coherent model [1, 2] in which the ME effect leads to the energy gain for switching exchange bias polarity. The asymmetry of EH_{th} between N-to-P and P-to-N was attributed to the uniaxial nature of magnetic anisotropy of AFM layer and the unidirectional nature of exchange coupling of the FM layer. The detail of the dependence of E_{th} on magnetic field (magnetic field and direction) will be discussed in the presentation.

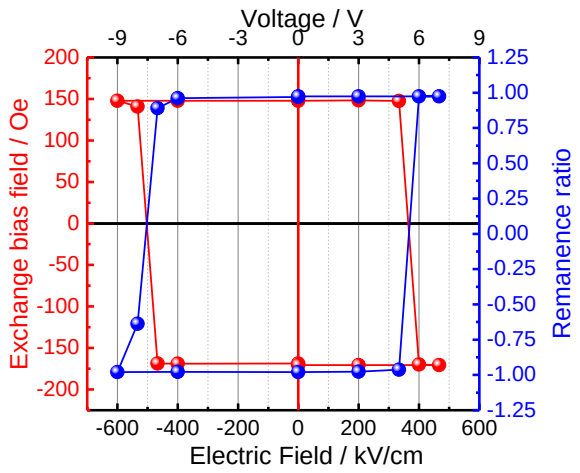

Fig. 1: Hysteretic electric field dependence of the exchange bias field (left) and remanence ratio (right) under -60 kOe at 275 K.

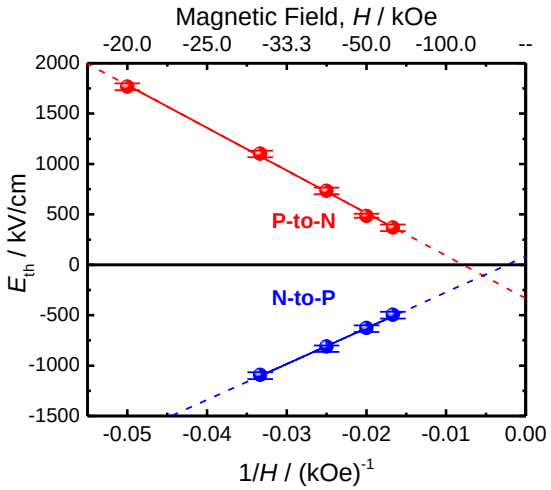

Fig. 2: Magnetic field dependence of threshold electric field E_{th} for switching exchange bias polarity measured at 275 K.

References

1) X. He et al., Nature Mat. **9**, 579, (2010).
2) K. Toyoki et al., Appl. Phys. Lett. **106**, 162402, (2015).

Al 置換による電気磁気材料 Cr_2O_3 薄膜の磁気異方性向上

野崎友大、塩川陽平、S. P. Pati、葉術軍、M. Al-Mahdawi、佐橋政司
（東北大学）

Enhanced magnetic anisotropy of magnetoelectric Cr_2O_3 film by Al-doping

T. Nozaki, Y. Shiokawa, S. P. Pati, S. Ye, M. Al-Mahdawi, and M. Sahashi
(Tohoku University)

序論

電気磁気材料である Cr_2O_3 は電圧による磁化反転を可能とする電気磁気効果デバイス、電圧制御 HDD や MRAM の候補として注目を集めている。近年、Cr_2O_3/Co 薄膜を用いた系で垂直交換バイアスの電界制御が実現されたことから [1,2]、実用化がより現実味を帯びてきている。しかし Cr_2O_3/Co 交換結合膜では、Cr_2O_3 の磁気異方性が低い($K_{AF} \sim 2 \times 10^5$ erg/cc)ため、特に薄い Cr_2O_3 薄膜を用いた場合に、交換バイアスのブロッキング温度がネール温度よりも大幅に下がってしまうことが問題となっている。我々は Cr_2O_3 と同じコランダム構造を持つ a-Fe_2O_3 薄膜への Ir 少量置換による垂直磁気異方性の向上に成功しており [3,4]、本研究では元素置換による Cr_2O_3 薄膜の磁気異方性の向上を目指した。

実験方法

膜構成は Al_2O_3 基板/Pt 25/Cr_2O_3 または Al-doped Cr_2O_3 t_{Cr2O3}/Co 1/Pt 5 (nm)である。(Al 置換)Cr_2O_3 薄膜は Cr または Al-Cr 合金ターゲットを用い、反応性スパッタ法で作製した。薄膜の Al 組成は XRF により確認した。Al 5atm%の Al-Cr 合金ターゲットを用いて作製した薄膜の Al 含有量は 3.7atm%程度であった。磁気特性の評価には SQUID 磁力計を用いた。

実験結果

図 1 に無置換試料および Al 置換試料の交換バイアスの温度依存性を示す。無置換試料では Cr_2O_3 薄膜の膜厚が 250nm であっても、その小さな磁気異方性と大きな交換バイアスのため、ブロッキング温度は 130K 程度とネール温度~300K よりもかなり小さい値となった。それに対して、Al 置換試料では、膜厚が同じ程度であるにも関わらず 280K 程度の大きなブロッキング温度が得られた。さらに、交換バイアスの大きさ自体も無置換試料よりも高い値が得られ、最大で 4500Oe を超える巨大な交換バイアスが得られた。Meiklejohn -Bean のモデルによるとブロッキング温度は磁気異方性が大きいほど、また、交換バイアスの大きさが小さいほど大きくなることから、Al 置換試料では大幅な磁気異方性の増大が起こっていると考えられる。このような磁気異方性の増大は、電気磁気効果デバイスの熱安定性を確保するためにも不可欠である。

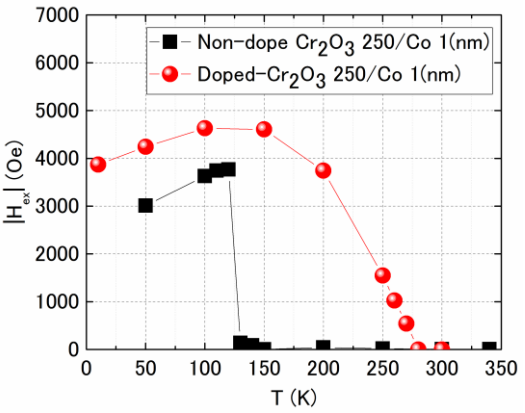

図 1 無置換試料および Al 置換試料の交換バイアスの温度依存性.

謝辞

本研究の一部は内閣府 ImPACT プログラムの支援を受けて行われた。

参考文献

1) T. Ashida *et al.*, Appl. Phys. Lett. **104** (2014) 152409.
2) T. Ashida *et al.*, Appl. Phys. Lett. **106,** (2015) 132407.
3) N. Shimomura *et al.*, J. Appl. Phys. **117** (2015) 17C736.
4) T. Mitsui *et al.*, J. Phys. Soc. Jpn., **85** (2016) 063601.

Effect of heavy metal doping on the Morin transition of epitaxial a-Fe_2O_3 (0001) thin films

M. A. Tanaka, K. Mikami, S. Ando and K. Mibu
(Nagoya Institute of Technology)

Hematite (a-Fe_2O_3), which is an antiferromagnetic material with high Néel temperature (T_N = 950 K), is attracting great interest, because this material can be applied for assisting layer of perpendicular magnetic devices, e.g., electric-field-writing-hard-disk drives. In pure a-Fe_2O_3, the Morin transition, which is the antiferromagnetic to weak ferromagnetic transition, occurs at 253 K, so that c-axis oriented a-Fe_2O_3 thin films have the in-plane spin configuration and show weak ferromagnetism at room temperature. Recently, Shimomura *et al.* reported that the Morin transition temperature (T_M) can be enhanced above 400 K in c-axis oriented a-Fe_2O_3 thin films by doping 1% Ir [1]. The Morin transition can be explained by the competition between magnetic dipolar anisotropy K_{MD} and single ion anisotropy K_{FS}. The enhancement of T_M is caused by the increase of K_{FS}. In this study, we report the heavy-metal-doping effect for Morin transition of c-axis oriented a-Fe_2O_3 thin films.

Heavy metal (Ru, Ir and W) doped a-Fe_2O_3 films of about 80 nm in thickness were deposited on Al_2O_3(0001) substrates by pulsed laser deposition method at various substrate temperatures in background oxygen pressure of 10 Pa. X-ray diffraction (XRD) measurement and conversion electron Mössbauer spectroscopy were performed for these samples at room temperature.

XRD measurement clarified that the growth direction of the heavy-metal-doped a-Fe_2O_3 films on Al_2O_3(0001) substrates was along c-axis. Figure 1 shows the Mössbauer spectra of 5% Ru doped a-Fe_2O_3 films deposited at the substrate temperature of 300°C, 400°C and 500°C. The angle q between the average spin direction and the vertical axis of film plane can be estimated by the intensity ratio of the six peaks of the Mössbauer spectra. When the spin direction is perpendicular to the film plane (q = 0°), the peaks indicated by the arrows disappear. The results show the peaks indicated by red arrows decrease with increasing growth temperature. The Mössbauer spectra indicated that the spin direction of 5% Ru doped a-Fe_2O_3 films deposited at the substrate temperature of 300°C is nearly in-plane (q = 76°) and that the T_M is below room temperature, while the spin direction of the 5% Ru doped a-Fe_2O_3 films deposited at the substrate temperature of 500°C is almost perpendicular (q = 16°) and the T_M is higher than room temperature. The spin direction angle of 5% Ru doped a-Fe_2O_3 films deposited at the substrate temperature of 300°C is 31°, indicating that the T_M of this sample is near room temperature. These results imply that the lattice location of Ru ions in a-Fe_2O_3 films varies with changing deposition temperature and that the difference of spin-orbit interaction of Ru ions affects the enhancement of K_{FS}.

In this presentation, we will also demonstrate the effect of other heavy metal (Ir and W) doping on Morin transition of a-Fe_2O_3 films.

This work was supported by ImPACT “Achieving ultimate Green IT Devices with long usage times without charging” of JST.

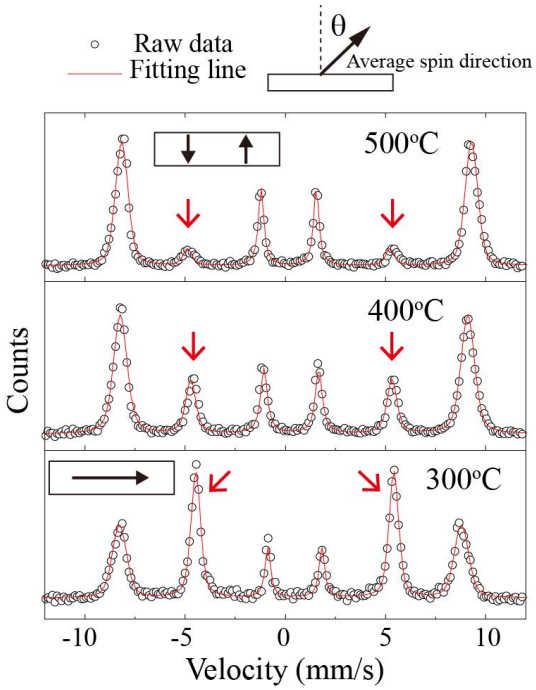

Fig. 1 Mössbauer spectra of 5% Ru doped a-Fe_2O_3 films deposited at the substrate temperature of 300°C, 400°C, and 500°C

Reference

1) N. Shimomura *et al.*, J. Appl. Phys., **117**, 17C736 (2015).