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.

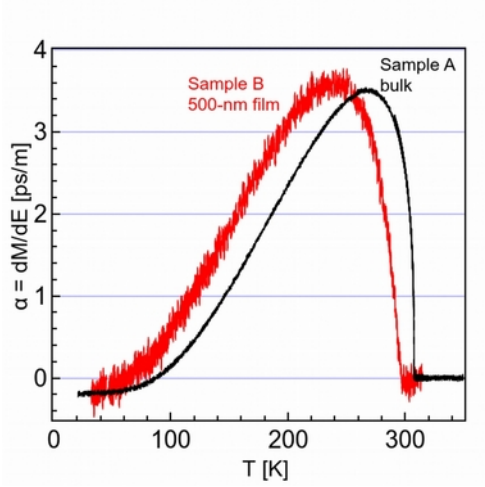

Fig. 1 Temperature-dependence of α in samples A and B

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.

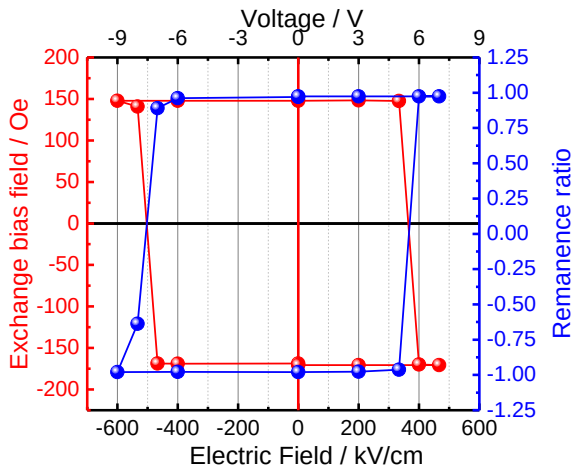

Fig. 1: Hysteretic electric field dependence of the exchange bias field (left) and remanence ratio (right) under -60 kOe at 275 K.

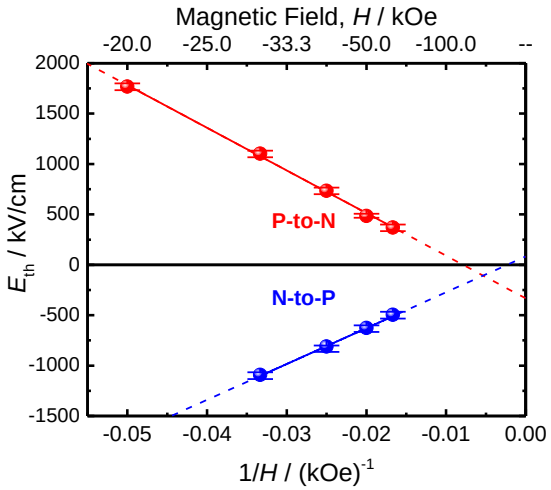

Fig. 2: Magnetic field dependence of threshold electric field E_{th} for switching exchange bias polarity measured at 275 K.

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。

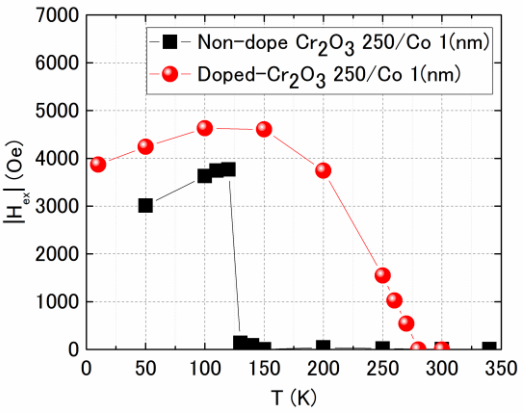

図 1 無置換試料および Al 置換試料の交換バイアスの温度依存性.

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.

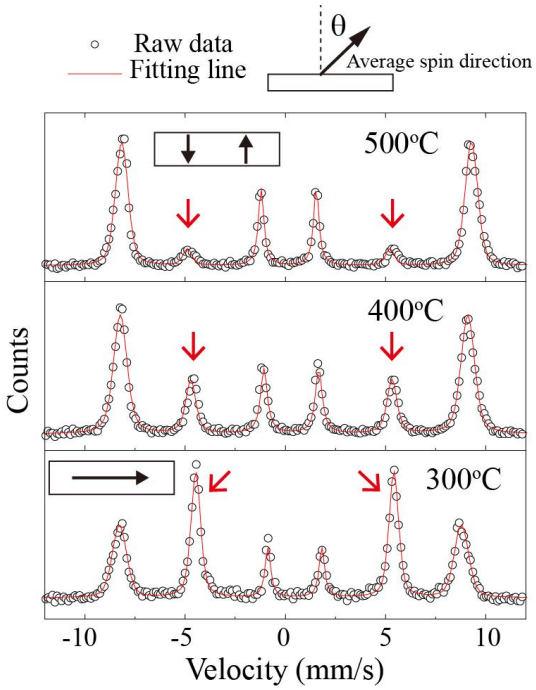

Fig. 1 Mössbauer spectra of 5% Ru doped a-Fe_2O_3 films deposited at the substrate temperature of 300°C, 400°C, and 500°C

Reference

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

Challenges toward voltage-torque MRAM

Shinji Yuasa
(AIST, Spintronics Research Center)

A magnetic tunnel junction (MTJ) consisting of a thin insulating layer (a tunnel barrier) sandwiched between two ferromagnetic electrodes exhibits the tunnel magnetoresistance (TMR) effect due to spin-dependent electron tunneling. Since the discovery of room-temperature TMR,[1,2] MTJs with an amorphous aluminum oxide (Al–O) tunnel barrier, which exhibit magnetoresistance (MR) ratios of several tens percent, have been studied extensively. In 2004, MR ratios of about 200% were obtained for fully epitaxial MTJs with single-crystal MgO(001) tunnel barrier [3] and textured MTJs with (001)-oriented MgO tunnel barrier[4]. MTJs with a CoFeB/MgO/CoFeB structure were also developed for practical application.[5] In the CoFeB/MgO/CoFeB MTJ, a highly textured MgO(001) barrier layer is grown on an amorphous CoFeB bottom electrode layer. By post-annealing the MTJs, the amorphous CoFeB layers are crystallized in bcc(001) structure due to the solid-phase epitaxial growth from the MgO interfaces[6]. Then, the (001)-textured CoFeB/MgO/CoFeB MTJ exhibit giant MR ratios as well as other practical properties such as low resistance-area (RA) product [7,8] and/or interfacial perpendicular magnetic anisotropy (PMA).[9] Because of the high manufacturability and practical magneto-transport properties, the CoFeB/MgO/CoFeB MTJs are widely used as the read heads of hard disk drives (HDDs), memory cell of non-volatile memory (STT-MRAM) especially with perpendicular magnetization, spin-torque oscillator (STO), and physical random number generator (Spin Dice).[10,11]

Although the textured CoFeB/MgO/CoFeB MTJs have been very successful, the properties are not sufficient for future device applications. Novel voltage-driven MRAM or voltage-torque MRAM based on voltage-induced dynamic switching [11] requires not only very high MR ratio (>>300%) but also very large voltage-control of magnetic anisotropy (VCMA) effect and PMA at the same time.[12] For satisfying these requirements, we need to develop novel MTJs with new materials for barrier and magnetic layers by using epitaxial growth on Si substrate as well as the wafer bonding and three-dimensional integration technologies to integrate the epitaxial MTJs in practical LSI. This paper summarizes challenges toward the voltage-torque MRAM.

This work was supported by the ImPACT Program of the Council for Science, Technology and Innovation.

Reference

1) T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **139**, L231 (1995).
2) J. S. Moodera, L. R. Kinder, T. M. Wong and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).
3) S Yuasa, T Nagahama, A Fukushima, Y Suzuki and K Ando, Nature Mater. **3**, 868 (2004).
4) S. S. P. Parkin *et al*., Nature Mater. **3**, 862 (2004).
5) D. D. Djayaprawira *et al*., Appl. Phys. Lett. **86**, 092502 (2005).
6) S. Yuasa and D. D. Djayaprawira, J. Phys. D: Appl. Phys. **40**, R337 (2007).
7) K. Tsunekawa *et al*., Appl. Phys. Lett. **87**, 072503 (2005).
8) Y. Nagamine *et al*. Appl. Phys. Lett. **89**, 162507 (2006).
9) S. Ikeda *et al*., Nature Mater. **9**, 721 (2010).
10) A. Fukushima *et al*., Appl. Phys. Express **6**, 083001 (2014)
11) Y. Shiota *et al*., Nature Mater. **11**, 39 (2012).
12) S. Yuasa *et al*., IEDM Tech. Dig. 3.1 (2014).

Large voltage-controlled magnetic anisotropy change in epitaxial Cr/ultrathin Fe/MgO/Fe magnetic tunnel junctions

Takayuki Nozaki[1], Anna Kozioł-Rachwał[1,2], Witold Skowroński[1,2], Vadym Zayets[1], Yoichi Shiota[1], Shingo Tamaru[1], Hitoshi Kubota[1], Akio Fukushima[1], Shinji Yuasa[1], and Yoshishige Suzuki[1,3]
(1 AIST, Spintronics Research Center, 2 AGH Univ., 3 Osaka Univ.)

Technological development in electric-field control of magnetic properties is strongly demanded to realize novel spintronic devices with ultralow operating power. Voltage-controlled magnetic anisotropy (VCMA) effect in an ultrathin ferromagnetic metal layer[1), 2)] is the most promising approach, because it can be applied in MgO based magnetic tunnel junction (MTJ). We have demonstrated fast speed response of VCMA effect through the voltage-induced ferromagnetic resonance[3)] and pulse-voltage induced dynamic magnetization switching[4)] so far. One of the outstanding technical issues in the VCMA effect is the demonstration of scalability. For example, for the development of G-bit class memory applications, high VCMA coefficient of more than 1000 fJ/Vm is required with sufficiently high thermal stability. However, the VCMA effect with high speed response is limited to be about 100 fJ/Vm at present.[5)]

In this study, we investigated the VCMA effect in an ultrathin Fe layer sandwiched between epitaxial Cr(001) buffer and MgO(001) barrier layers.[6)] High interface anisotropy energy, $K_{i,0}$ of about 2 mJ/m^2 was recently demonstrated in Cr/ultrathin Fe/MgO structure,[7)] probably due to the atomically flat interfaces and suppression of surface segregation from the buffer material. We applied this structure in the voltage-driven MTJ and performed systematic investigations on perpendicular magnetic anisotropy (PMA) and VCMA effect through the tunnel magnetoresistance (TMR) properties. Fully epitaxial MTJ of MgO seed (3 nm)/Cr buffer (30 nm)/ultrathin Fe (t_{Fe})/MgO (t_{MgO})/Fe (10 nm)/Ta/Ru were deposited on MgO (001) substrates by molecular beam epitaxy. Here, the ultrathin Fe layer is the voltage-controlled free layer with perpendicular magnetic easy axis and top thick Fe layer is the reference layer with in-plane magnetic easy axis. The PMA energy, K_{PMA} and VCMA properties were evaluated from the normalized TMR curves measured under in-plane magnetic fields with various bias voltage applications. Saturation magnetization value was obtained by SQUID measurement.

High interface anisotropy energy, $K_{i,0}$ of 2.1 mJ/m^2 was confirmed in our sample. Figure 1 shows an example of applied electric field dependene of surface anisotropy energy, $K_{PMA}t_{Fe}$ for the MTJ with t_{Fe} = 0.45 nm and t_{MgO} = 2.8 nm. We observed large VCMA coefficient of about 400 fJ/Vm under the negative electric field application, while non-linear behavior appeared under the positive direction. In the presentation, we'll discuss the possible origin of the enhanced VCMA effect and non-linearity including the evaluation results of structural analysis at the Cr/ultrathin Fe/MgO interfaces.

This work was partly supported by ImPACT Program of Council for Science, Technology and Innovation, the Strategic AIST integrated R&D program "IMPULSE", and a Grand-in-Aid for Scientific Research (No. 26709046).

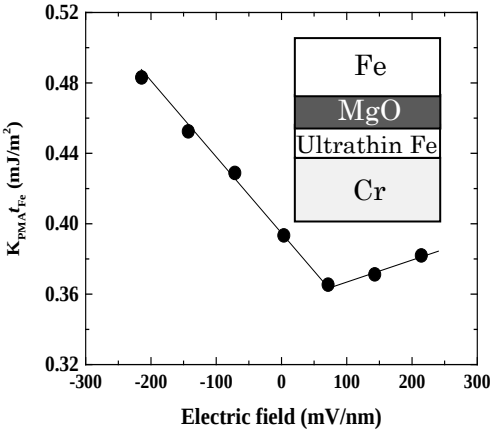

Figure 1 Example of VCMA effect observed in epitaxial Cr/ultrathin Fe/MgO/Fe MTJ with t_{Fe}=0.45 nm and t_{MgO} = 2.8 nm. Perpendicular magnetic anisotropy, K_{PMA} was evaluated from normalized TMR curves and saturation magnetization value measured by SQUID.

Reference

1) M. Weisheit *et al*. *Science* **315**, 349 (2007).
2) T. Maruyama *et al. Nature Nanotech*. **4**, 158 (2009).
3) T. Nozaki *et al. Nature Phys.* **8**, 491 (2012).
4) Y. Shiota *et al. Nature Mater.* **11**, 39 (2012).
5) T. Nozaki *et al. Appl. Phys. Exp*. **7**, 073002 (2014).
6) T. Nozaki *et al*. *Phys. Rev. Appl.* **5**, 044006 (2016).
7) J. W. Koo *et al*. *Appl. Phys. Lett.* **103**, 192401 (2013).

Write error rate of voltage-driven dynamic magnetization switching

Yoichi Shiota[1], Takayuki Nozaki[1], Shingo Tamaru[1], Tomohiro Taniguchi[1], Kay Yakushiji[1], Hitoshi Kubota[1], Akio Fukushima[1], Shinji Yuasa[1], and Yoshishige Suzuki[1,2]
(1 AIST, Spintronics Research Center, 2 Osaka Univ.)

Voltage-control of magnetic anisotropy [1,2] is a promising technique for ultimate spintronic devices with ultra-low power consumption. To apply the voltage-induced magnetic anisotropy change to the writing process, the dynamic magnetization switching triggered by the sub-ns pulse voltage has been demonstrated. [3,4] One of the important issues for the practical application is the evaluation and improvement of the write error rate (WER). However precise control of the magnetization dynamics is not easy because the proper pulse duration is about 1ns or shorter. In this study, we investigated the WER of voltage-induced dynamic magnetization switching in perpendicularly magnetized magnetic tunnel junctions (p-MTJs). [5]

A film for p-MTJ, consisting of buffer layer / [Co (0.24 nm)/Pt (0.16 nm)]^7 / Co (0.24 nm) / Ru (0.46 nm) / [Co (0.24 nm)/Pt (0.16 nm)]^5 / CoB (0.4 nm) / W (0.15 nm) / $Co_{12}Fe_{68}B_{20}$ (1.0 nm) / MgO barrier / FeB (1.8 nm) / W (2.0 nm) / cap layer, was prepared by using ultra-high vacuum sputtering machine (Canon-Anelva C-7100). The film was annealed at 350°C for 1 hour and micro-fabricated into a 120-nm-diameter p-MTJ. The magnetoresistance ratio and resistance-area product are 101% and 370 Ω·μm^2, respectively. We investigated the WER from the 10^5 repeated events at various conditions of pulse duration and pulse amplitude and external magnetic field.

First, we observed the bidirectional switching and oscillatory behavior of switching probability. These results clearly indicate that the observed switching originates from the voltage-induced magnetic anisotropy change. Figures 1 (a) – (c) show the WER as a function of pulse duration under different conditions of the in-plane magnetic field strength. The minimum of WER, $(WER)_{min}$, was obtained at the half period of the magnetization precession, which becomes shorter as increasing the in-plane magnetic field. Increase of switching time results in low $(WER)_{min}$ because the effect of thermal agitation becomes negligible. However further increase of an in-plane magnetic field increases the $(WER)_{min}$ due to the reduction of thermal stability factor. Under the optimized condition, the lowest $(WER)_{min}$ of 4×10^{-3} was obtained as shown in Fig. 1 (b). The comparison between the results of the experiment and simulation based on a macro-spin model shows a possibility of ultralow WER ($< 10^{-15}$).

This work was partly supported by ImPACT Program of Council for Science, Technology and Innovation, and a Grand-in-Aid for Scientific Research (No. 26886017).

Reference

[1] M. Weisheit *et al.*, *Science* **315**, 349 (2007), [2] T. Maruyama *et al.*, *Nature Nanotechnol.* **4**, 158 (2009), [3] Y. Shiota *et al.*, *Nature Mater.* **11**, 39 (2012), [4] S. Kanai *et al.*, *Appl. Phys. Lett.* **101**, 122403 (2012), [5] Y. Shiota *et al.*, *Appl Phys. Express* **9**, 013001 (2016)

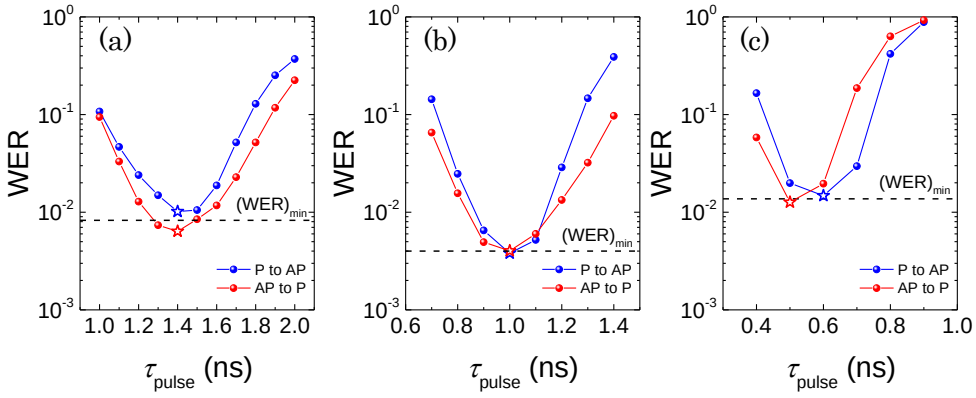

Figure 1　Write error rate (WER) as a function of pulse duration under in-plane magnetic fields of (a) 14 mT, (b) 20 mT, and (c) 38 mT. Blue and red curves represent the WER from P to AP state and AP to P state, respectively.

高次の磁気異方性を有する自由層の磁化反転特性

松本利映 *, 荒井礼子 **,*, 湯浅新治 *, 今村裕志 *
(* 産総研, **JST さきがけ)

Magnetization switching property in a free layer having higher-order magnetic anisotropy

R. Matsumoto*, H. Arai**,*, S. Yuasa*, and H. Imamura*
(*AIST, **JST-PRESTO)

1　はじめに

CPU の SRAM や DRAM を置き換えるための STT-MRAM を開発するためには, その熱耐性 (Δ_0) を 60 以上に保持しつつスピントランスファー・トルク磁化反転の閾値電流密度 (J_{sw}) を 1 MA/cm^2 以下に低減させることが求められる. 最近我々は, 等しい熱耐性 Δ_0(=60) で比較した場合, コーン磁化の自由層 (c-FL) は従来の垂直磁化の自由層より閾値電流密度は 22% 小さく磁化反転時間は 56% 短くなることなど, c-FL の優位性を理論的に明らかにしてきた [1,2]. コーン磁化とは, 低次の磁気異方性 (その定数を $K_{u1,eff}$ と呼び, 反磁場エネルギーを含めたものとする) と高次の磁気異方性 (その定数を K_{u2} と呼ぶ) の競合で発現する磁化状態で, その磁化は面内方向と面直方向の間の方向を向く. コーン磁化にならずとも K_{u2} は J_{sw} 低減に有利であると考えられる. 本研究では, K_{u2} を有する自由層を利用した STT-MRAM 素子の Δ_0 と J_{sw} を解析的に計算し, その効果を調べた.

2　結果および考察

本研究で考慮する STT-MRAM 素子を図 1(a) に図示した. 参照層は垂直磁化で, 自由層は垂直磁化かコーン磁化である. 極角 (θ) は z 軸から測った角度である. 正の電流のとき電子 (電気素量を e とする) は自由層から参照層へ流れる.

自由層のエネルギー密度 (ϵ) は次のように書き表される : $\epsilon = K_{u1,eff}\sin^2\theta + K_{u2}\sin^4\theta$. 図 1(b) に磁化状態の $K_{u1,eff}$, K_{u2} 依存性を示している. $K_{u1,eff} < 0$ かつ $K_{u2} > -(1/2)K_{u1,eff}$ のときにコーン磁化が安定状態となる. $K_{u1,eff} > 0$ のときに垂直磁化が安定状態か準安定状態となる.

Δ_0 の解析式は ϵ から得られる. 図 1(c) の ① の領域すなわち $[K_{u1,eff} < 0$ かつ $K_{u2} > -(1/2)K_{u1,eff}]$ のとき $\Delta_0 = \left(K_{u1,eff} + K_{u2} + \frac{K_{u1,eff}^2}{4K_{u2}}\right)V/(k_BT)$, ② の領域すなわち $[K_{u1,eff} > 0$ かつ $K_{u2} \geq -(1/2)K_{u1,eff}]$ のとき $\Delta_0 = (K_{u1,eff} + K_{u2})\,V/(k_BT)$, ③ の領域すなわち $[K_{u1,eff} > 0$ かつ $K_{u2} \leq -(1/2)K_{u1,eff}]$ のとき $\Delta_0 = \left[-K_{u1,eff}^2/(4K_{u2})\right]V/(k_BT)$ である [3]. 解析式から計算した Δ_0 の $K_{u1,eff}$, K_{u2} 依存性を図 1(d) に示す. $K_{u1,eff}$ と K_{u2} は大きいほど Δ_0 は大きい.

J_{sw} の解析式はランダウ-リフシッツ-ギルバート方程式から得られる. 図 1(e) の ① の領域すなわち $[K_{u1,eff} > 0$ かつ $K_{u2} \geq (1/4)K_{u1,eff}]$ または $[K_{u1,eff} < 0$ かつ $K_{u2} > -(1/2)K_{u1,eff}]$ のとき $J_{sw} = \frac{8}{3\sqrt{6}}\frac{\alpha d|e|}{\hbar P}\sqrt{\frac{(K_{u1,eff}+2K_{u2})^3}{K_{u2}}}$ であり, $K_{u1,eff}$ と K_{u2} は大きいほど J_{sw} も大きい. 一方で ② の領域すなわち $[K_{u1,eff} > 0$ かつ $K_{u2} \leq (1/4)K_{u1,eff}]$ のとき $J_{sw} = 4\frac{\alpha d|e|}{\hbar P}K_{u1,eff}$ であり、J_{sw} は $K_{u1,eff}$ のみに比例する. 解析式から計算した J_{sw} の $K_{u1,eff}$, K_{u2} 依存性を図 1(f) に示す. 図 1(e), (f) から $[K_{u1,eff} > 0$ かつ $0 < K_{u2} \leq (1/4)K_{u1,eff}]$ のときは、K_{u2} は Δ_0 の上昇に寄与するものの J_{sw} を上昇させないことがわかる. Δ_0 を保持させつつ J_{sw} を低減させる観点からはこの領域が最も有利であると考えられる.

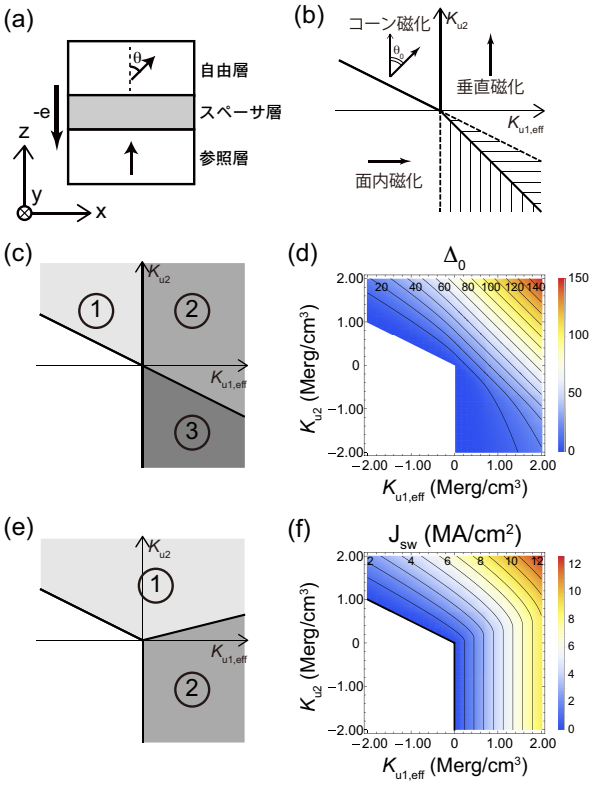

Fig. 1　(a) STT-MRAM 素子の模式図. (b): 磁化状態, (c), (d): Δ_0, (e), (f): J_{sw} の $K_{u1,eff}$, K_{u2} 依存性. (c) と (e) は解析式の区分を表す.

References

1) R. Matsumoto, H. Arai, S. Yuasa, and H. Imamura: *Appl. Phys.Express*, **8**, 063007 (2015).
2) R. Matsumoto, H. Arai, S. Yuasa, and H. Imamura: *Phys. Rev. B*, **92**, 140409(R) (2015).
3) 本文中の数式における記号の意味は次の通りである : V と d は自由層の体積と厚さ, k_B はボルツマン定数, T は絶対温度, α はギルバート・ダンピング定数, $\hbar$ はディラック定数, P はスピン分極率.

Deep etching microfabrication of perpendicularly magnetized MTJ

Akio Fukushima, Kay Yakushiji, Hitoshi Kubota, Shinji Yuasa
(AIST, Spintronics Research Center)

Low damage microfabrication is one of the most importance issue to fabricate higher density magnetic memory devices. Etching process of the pillar part of magnetic tunnel junction (MTJ) is thought to be the main origin of the processing damage. Argon ion beam etching has been used widely to fabricate the pillar part of MTJs because its etching rate is not much sensitive to film materials. Reduction of the beam voltage of Ar ion beam etching is a straight way to decrease the processing damage. Here, we report the deep etching microfabrication using low voltage Ar ion beam etching, and some of the deep etched MTJs show enhancement of coercive field (H_c) and keep thermal activated energy (Δ).

We introduced new fabrication machine which is combining one etching chamber and two deposition chambers. This machine makes possible to etch the pillar of MTJs and then to transfer the deposition chamber without breaking the vacuum. The beam voltage and current of Ar ion beam is set to 150V and 45 mA, respectively. Low resistance perpendicularly-magnetized MTJs [1] were used to estimate the process damage. We prepared a film of perpendicularly-magnetized MTJ, which is consisting of buffer layer / [Co (0.24 nm)/Pt (0.16 nm)]^9 / Co (0.24 nm) / Ru (0.52 nm) / [Co (0.24 nm)/Pt (0.16 nm)]^4 / W (0.1 nm) / CoB (0.4 nm) / W (0.1 nm) / FeB (1.1 nm) / MgO barrier / FeB (~2 nm) / MgO cap / cap layer by ultra-high vacuum sputtering machine (Canon-Anelva C-7100). The top of the buffer layer is about 50 nm-thick Ta layer. The film was annealed at 330°C for 1 hour, and then microfabricated into circular MTJs with etching masks of 85, 75, 65 nm diameters. The resistance-area (RA) product of the film was 2.0 $\Omega\cdot\mu m^2$.

Two etching processes are tested; the first is standard etching where the MTJ film was etched down to just top of the buffer layer; and the second is deep etching where the film was over etched into the middle of the buffer layer. The etching depth was monitored by secondary ion mass spectrometer, but we need to care that the etching depth near the pillar tends to be smaller than that of the plane part. The typical etching time for the standard etching is 30 min. and that for the deep etching is about 50 min. After that, the pillar was covered by SiO_2 layer without breaking the vacuum, and then lift-offed the etching mask and made the top electrode.

For both cases, the magnetoresistance (MR) ratios of the MTJs were 110~120% and well coincident. Diameters of the MTJs were estimated from the resistance of parallel state and the RA value. Reduction of the diameter was about 15nm for standard etching and that was about 25 nm for deep etching. We found the deep etched MTJs tend to have larger coercive field (H_c) that standard etched one and those MTJs have relative large thermal activation energy (Δ) where Δ was evaluated from the current dependence to the switching probability [2].

This work was supported by ImPACT Program of Council for Science, Technology and Innovation.

Reference

[1] K. Yakushiji *et al.*, Appl. Phys. Express 6 (2013) 113006, [2] Edited by T. Shinjo, "Nanomagnetims and Spintronics" (1st edition, Elsevier), Authors: Y. Suzuki, A. A. Tulapurkar, and C. Chappert, Chap. 3 (2009).

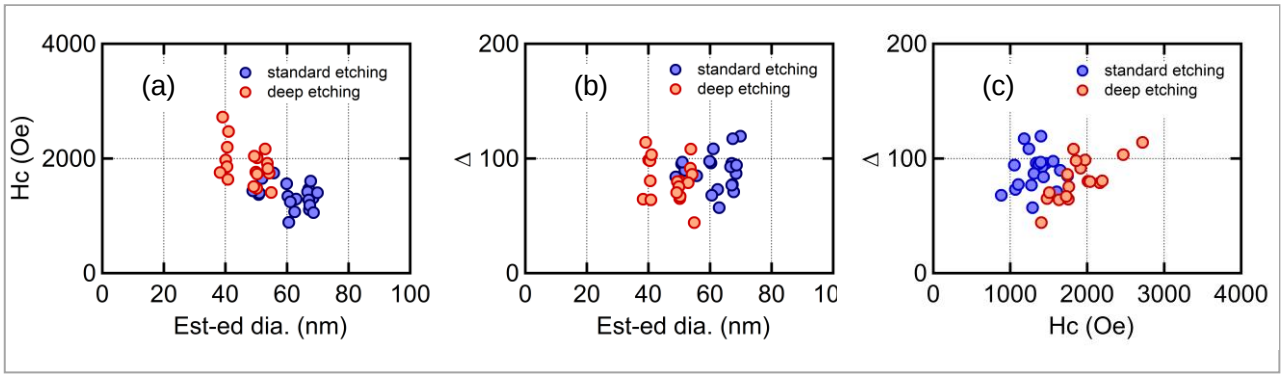

Figure 1 Relationships between (a) estimated diameter of MTJ and H_c, (b) estimated diameter and Δ, (c) H_c and Δ.

Spintronics devices for nonvolatile VLSI

Hideo Ohno[1-5]

[1] Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku University, Sendai 980-8577 Japan
[2] Center for Spintronics Integrated Systems, Tohoku University, Sendai 980-8577 Japan
[3] Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai 980-0845 Japan
[4] Center for Spintronics Research Network, Tohoku University, Sendai, 980-8577 Japan
[5] WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577 Japan

Here I review two- and three-terminal nano-spintronics nonvolatile devices for VLSI integration. VLSIs can be made high performance and yet standby-power free by using nonvolatile spintronics devices [1]. The most commonly employed device is magnetic tunnel junction (MTJ), a two-terminal spintronic device that can scale beyond 20 nm with perpendicular CoFeB-MgO [2,3]. I will describe the development of such devices and its performance together with associated materials and physics issues. While two-terminal configuration is suitable for high density applications, three-terminal configuration allows high speed and relaxed VLSI design constraints compared to the two-terminal counterpart. Of particular interest are three-terminal devices that utilize spin-orbit torque (SOT) switching, which does not require an antiferromagnetically aligned pair of magnetic electrodes as in current-induced domain wall motion devices [4]. On this front, I will discuss high speed operation of an SOT switching device with a target ferromagnetic pillar having an out-of-plane easy axis [5] or an in-plane magnetic easy axis collinear with the current flow direction in the underneath heavy-metal [6]. The magnetization switching is achieved with 500-ps pulses, which is not readily available in two-terminal devices utilizing spin-transfer torque (STT) switching, because STT requires switching current inversely proportional to the switching speed in this speed range. I then report the use of an antiferromagnetic material as a source of spin flow as well as the exchange field. Before, structures for fast SOT switching required a small constant external magnetic field to induce switching, which was an obstacle for application. It has been shown in a (Co/Ni)-multilayer/PtMn structure that one can switch magnetization in the absence of external magnetic field using PtMn as a source of spin [7], removing this obstacle. I summarize my talk by comparing two- and three-terminal device performance.

This work has been carried out with S. Fukami, H. Sato, F. Matsukura, S. Ikeda, and the CSIS team, and has been supported by the ImPACT Program of CSTI (PM Dr. Masashi Sahashi) and in part by the R&D Project for ICT Key Technology of MEXT.

1) H. Ohno, International Electron Device Meeting (IEDM) (invited) 9.4.1 (2010).
2) S. Ikeda, et al. Nature Materials, **9**, 721 (2010).
3) H. Sato, et al. IEDM 2013 and Appl. Phys. Lett. **105**, 062403 (2014).
4) S. Fukami, et al. IEDM 2013; Nature Comm. 4:2293 doi: 10.1038/ncomms3293 (2013); IEEE Trans. Magn. **50**, 34106 (2014); Phys. Rev. B **91**, 235401 (2015).
5) C. Zhang, et al., Appl. Phys. Lett., **107**, 012401 (2015).
6) S. Fukami, et al. Nature Nanotechnology, doi:10.1038/nnano2016.29 (2016).
7) S. Fukami, et al. Nature Materials, **15**, 535 (2016).

Low Power NV-Working Memory and NV-Logic with Spintronics/CMOS Hybrid ULSI Technology

T. Endoh[1,2,3,4], H. Koike[1], Y. Ma[1], T. Hanyu[1,3,4], S. Ikeda[1,3,4], and H. Ohno[1,3,4,5,6]

[1] Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai 980-0845 Japan
[2] Graduate School of Engineering, Tohoku University, Sendai, 980-8579 Japan
[3]Center for Spintronics Integrated Systems, Tohoku University, Sendai 980-8577 Japan
[4] Center for Spintronics Research Network, Tohoku University, Sendai, 980-8577 Japan
[5]Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku University, Sendai 980-8577 Japan
[6] WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577 Japan

In information and communication technology (ICT) equipment indispensable for modern society, semiconductor memories occupy the main position of silicon storage, working memories, and logic blocks. Semiconductor memories in ICT equipment normally constitute a pyramid-like structure from cache memory (SRAM), main memory (DRAM) to storage memory (NAND). In such current semiconductor memories, there are two key issues: (1) speed gap between different levels of the memory hierarchy and (2) rapid increase in the power consumption because of the increased density. In order for ICT technology to keep contributing for the world society under the situation, where the more energy-saving is strongly required, it is essential to develop and commercialize LSIs which achieve both reduction of power dissipation and enhancement of speed performance.

In this invited talk, it is reviewed material and STT-MRAM device technology including the basics of MTJ device. Especially, our recent development results of spintronics LSIs are reviewed. We discuss STT-MRAM including the fast differential type STT-MRAM and the high-density 1T1MTJ type STT-MRAM, and then move onto MTJ based Nonvolatile (NV-) Logic LSIs. From these results, it is shown that STT-MRAM will solve both issues of speed gap and power consumption simultaneously. Next, from the background mentioned above, the directionality of the revolution in the semiconductor memory hierarchy structure is discussed. The realization of this revolution with STT-MRAMs is introduced. It is shown that our developed 1Mbit STT-MRAM fabricated with 90 nm CMOS and 70nm MTJ process, achieves Read/Write performance of 1.5nsec / 2.1nsec which is sufficient for cache memory application. Next, we show ultra-high speed 1Mbit STT-MRAM with developed differential type STT-MRAM cell (twin 1T-1MTJ cell technology), which achieves the read latency of 500 psec. Finally, NV-logic as one of application technology of leading edge memory technology is shown. It is discussed that power of MPU and Associative Processor for Image Pattern Recognition is extremely suppressed with spintronics based NV-logic technique

This work was supported in part by CIES's Industrial Affiliation on STT -MRAM Program, R&D Project for ICT Technology of MEXT, ImPACT Program of CSTI, and ACCEL Program under JST.

Reference

1) T. Endoh, et al. 2011 IEDM, pp.75-78, 2011.
2) T. Endoh, et al. Symposia on VLSI Circuits, pp89-90, 2012, (*Invited*)
3) T. Endoh, 2013 VLSI Technology Short Course of 2013 Symposium on VLSI, June 2013 (*Invited*)
4) T. Endoh, CMOS Emerging Technologies Research, MINATEC, 2014 (*Invited*)
5) H. Koike, et al. Jpn. J. Appl. Phys. 54, 04DE08, March 2015.
6) T. Endoh, 2016 MRS Spring Meeting & Exhibit, EP11.1.08, 2016 (*Invited*)
7) Y. Ma, et al., Japanese Journal of Applied Physics(JJAP),55(4S), 2016
8) H. Koike, et al., 2016 International Memory workshop, May 2016
9) T. Endoh et al., IEEE Journal on Emerging and Selected Topics in Circuit and Systems (JESCAS), 2016

Three-terminal spintronics devices with spin-orbit torque induced switching for ultra-low power and high-performance integrated circuits

S. Fukami[1-4], C. Zhang[1], S. DuttaGupta[1], A. Kurenkov[1], T. Anekawa[1], A. Ohkawara[1], and H. Ohno[1-5]

[1] Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku University, Sendai 980-8577 Japan
[2] Center for Spintronics Integrated Systems, Tohoku University, Sendai 980-8577 Japan
[3] Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai 980-0845 Japan
[4] Center for Spintronics Research Network, Tohoku University, Sendai, 980-8577 Japan
[5] WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577 Japan

Spintronics memory devices with three-terminal configuration are suitable for high-speed and high-reliability applications compared with the devices with two-terminal configuration, owing to their separated current paths between the read and write operations [1)]. Spin-orbit torque (SOT)-induced magnetization switching [2,3)] is a promising scheme for the write operation of the three-terminal devices. Here we show our recent studies on the SOT-induced switching which open new possibilities of the devices and integrated circuit technologies.

The previous studies on the SOT switching build on either of two structures, both of which have the magnetic easy axis of the free layer directing orthogonal to the current: perpendicular to the plane [2)] or in-plane and orthogonal to the channel current [3)]. We have recently shown the third switching scheme with the easy axis collinear with the current [4)]. The current-induced switching originating from the SOT with Slonczewski-like symmetry has been observed in a three-terminal device with the new structure, where a Ta/CoFeB/MgO-based stack is used. Importantly, this scheme can serve as a useful tool to investigate the physics of SOT-induced switching [4)] as well as an attractive option for the application to the integrated circuits [5)]. In the presentation, we show that the new scheme allows us to unambiguously discuss the factors that determine the SOT switching current density and the difference in the dynamics between the SOT and conventional spin-transfer-torque induced magnetization switching. We also show reliable switching achieved by current pulses with the duration of 500 ps and amplitude of 1.9×10^{11} A/m^2; this feature is highly promising for high-performance integrated circuits.

This work is partly supported by ImPACT Program of CSTI, R&D Project for ICT Key Technology of MEXT, and JSPS KAKENHI 15K13964 and 15J04691.

Reference

1) S. Fukami M. Yamanouchi, S. Ikeda, and H. Ohno, IEEE Trans. Magn., **50**, 3401006 (2014).
2) I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella *et al.*, Nature **476**, 189 (2011).
3) L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, Science **336**, 555 (2012).
4) S. Fukami, T. Anekawa, C. Zhang, and H. Ohno, Nature Nanotech., doi: 10.1038/nnano2016.29 (2016).
5) S. Fukami, T. Anekawa, A. Ohkawara, C. Zhang, and H. Ohno, 2016 Symp. on VLSI Tech., Dig. Tech. Pap., T6-5 (2016).

Room temperature growth of ultrathin ordered Mn-Ga films

○K. Z. Suzuki, R. Ranjbar, A. Sugihara, T. Miyazaki, and S. Mizukami
WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

$L1_0$-MnGa alloy films have a large perpendicular magnetic anisotropy and small damping constant[1] and it is potentially attractive for Spin-transfer-torque magnetoresistive random access memory (STT-MRAM) applications. Growth of ultrathin Mn-Ga films, whose thickness is usually less than 3 nm, is required for STT-switching, whereas it has been difficult.[2-5] Here we demonstrate the growth of ultrathin MnGa films with thickness down to 1 nm by using paramagnetic CoGa buffer layer having CsCl-type crystal structure. All the samples were prepared by a ultrahigh vacuum (UHV) magnetron sputtering system.

The sample stacking structure is MgO(001) substrate/Cr (40 nm)/CoGa (30 nm)/MnGa (t_{MnGa}=1-5)/Mg (0.4) /MgO (5). The Cr and CoGa buffer layers were deposited at room temperature and subsequently annealed at 700 and 500°C, respectively. The MnGa layer was deposited on the CoGa buffer layer at room temperature and not annealed. The out-of-plane polar Kerr loops for these films are shown in Fig. 1. The loops with squareness close to unity are observed even at t_{MnGa}= 1 nm.[6] Figure 2 shows a cross-sectional image of CoGa/MnGa/MgO layers measured by a high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). The atomically flat interfaces and well-ordered crystalline structure of the MnGa layer was observed.[7] These results indicate that the CoGa buffer layer is a promising candidate for growth of ultrathin film of Mn-based alloys. We will also discuss the spin-dependent transport properties.

This work was supported in part by NEDO, ImPACT program “Achieving ultimate Green IT Devices with long usage times without charging”, and Asahi glass foundations.

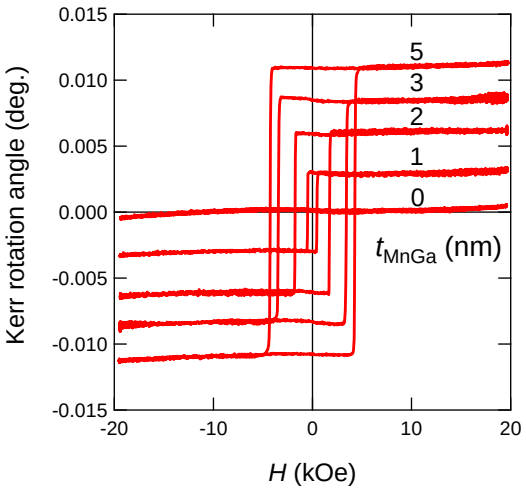

Fig. 1 Out-of-plane hysteresis curves for the ultrathin MnGa films with different thickness measured by polar magneto-optical Kerr effect.

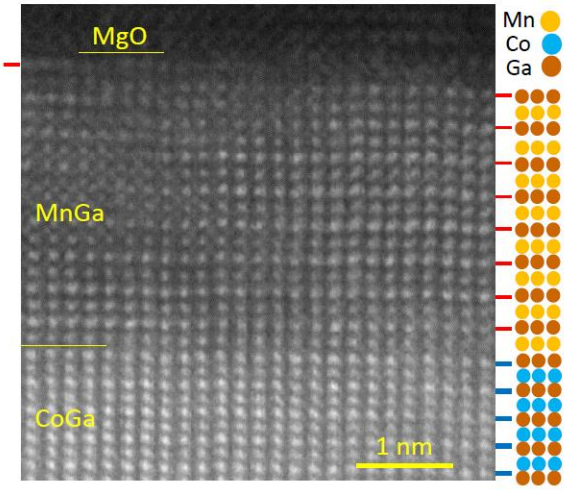

Fig.2 The cross-sectional HAADF-STEM image of the CoGa/MnGa/MgO layers. Right cartoon is the schematic for the corresponding to the atomic structures.

Reference

1) S. Mizukami et al, Phys. Rev. Lett. **106**, 117201 (2011).
2) F. Wu et al., IEEE Trans. Magn. **46**, 1863 (2010).
3) A. Kohler et al., Appl. Phys. Lett. **103**, 162406(2013).
4) M. Li, X. Jiang, et al., Appl. Phys. Lett. **103**, 032410 (2013).
5) Y. H. Zheng et al., J. Appl. Phys. **115**, 043902 (2014).
6) K.Z. Suzuki et al., Jpn. J. Appl. Phys. (RC) **55**, 010305 (2016).
7) K.Z. Suzuki et al. submitted, 2016.