Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp1193-1194

Mechanism of Electric Field Effect on Magnetism in Surface-Oxidized Co/Oxide Dielectric Layer

Takamasa Hirai[1], Tomohiro Koyama[1] and Daichi Chiba[1]

[1] The Univ. of Tokyo
7-3-1, Hongo, Bunkyo-ku
Tokyo 113-8656, Japan
Phone: +81-3-5841-1166 E-mail: thirai@cblb.t.u-tokyo.ac.jp

Abstract

We have studied the mechanism of electric field (EF) effect on magnetism in Pt/Co with naturally oxidized Co surface. By comparing the results for two samples with a HfO_2 dielectric layer fabricated under different conditions for atomic layer deposition (ALD), we found the dominant mechanism of the EF effect dramatically depends on the quality of the dielectric layer.

1. Introduction

The EF effect on magnetism in ultrathin 3*d* ferromagnetic metal (3*d*-FM)/oxide bilayer structures has been greatly attracted mainly from the viewpoint of application for spintronics devices and new controlling method of microscopic magnetic properties [1]. The most probable origin of this EF effect is the modification of electronic structure by charge carrier doping at the interface of 3*d*-FM/oxide [2,3]. On the other hand, thermal electrochemical reaction has been suggested as another mechanism [4,5]. For the future device application, clarifying these effects and making choice as necessary are required. In this talk, we show the result of the EF effect on the magnetic anisotropy and magnetic moment in a Co ultrathin film with a naturally-oxidized surface using solid-state capacitors with a gate insulator HfO_2 deposited under different conditions.

2. Sample fabrication method

Ta(3.3 nm)/Pt(3.0)/Co(1.0) stack was deposited on an intrinsic Si(001) substrate by rf sputtering at room temperature. After exposing it to the air for about 10 min, the film was covered with a 5-nm-thick HfO_2 in an ALD chamber at 150°C (sample A) and 60°C (sample B). Note that 150°C is within the appropriate temperature range of the ALD process and 60°C is far below it. Next, it was patterned into 30-µm-width Hall bar (for Hall measurement) or 2-mm square (for direct magnetization measurement) mesa structure. Subsequently, 40-nm-thick HfO_2 gate dielectric layer was formed using the ALD under each temperature condition. Finally, a Cr/Au/Cu top counter electrode was formed using lift-off process.

3. Results

Figure 1 shows a gate voltage (V_G), the coercive field (μ_0H_c), the squareness ratio of magnetic hysteresis (R_{Hall}^r/R_{Hall}^s), the 2-wire resistance ($R_{2\text{-wire}}$), and the gate leakage current (I_G) for each anomalous Hall (AH) measurement

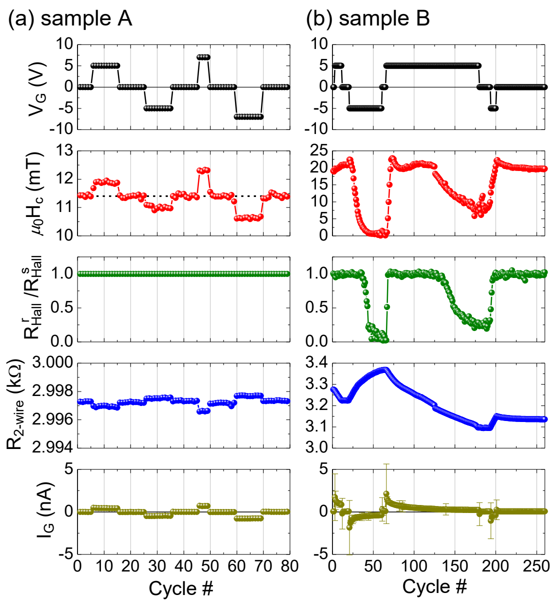

Fig. 1: V_G, μ_0H_c, R_{Hall}^r/R_{Hall}^s, $R_{2\text{-wire}}$, and I_G as a function of cycle for each AH measurement of (a) sample A and (b) B.

for samples A and B. The time required for one AH measurement is 35 sec and the measurement interval is 60 sec. In this study, positive (negative) V_G corresponds to the direction of the charge accumulation (depletion) at Co/oxide interface. At initial state of the gating process, both samples have clear out-of-plane easy axis ($R_{Hall}^r/R_{Hall}^s = 1$) as shown in Fig. 2. In sample A, small but reversible change in μ_0H_c and $R_{2\text{-wire}}$ following to V_G value can be observed. The ratio of $R_{2\text{-wire}}$ change is slightly small (~0.02%), and the squareness is remained to be 1. This means the effect of electrostatic charge accumulation is dominant in EF effect in sample A. The capacitance (C) – frequency (f) and the phase angle (θ) – frequency (f) relation in sample A show a conventional capacitor property, which supports above conclusion.

In contrast, in sample B, the drastic and unusual change can be seen. The modulation of $R_{2\text{-wire}}$ is much larger (~10%) and μ_0H_c greatly changes in the range of ~20 mT to 0 T. The magnetism of sample B can be controlled from paramagnetic-state (cycle ~#50) to in-plane-easy-state (cycle ~#160) (see in Fig. 2), depending on V_G. Moreover, magnetic properties are not immediately altered but gradually modulated after V_G is changed. The magnetic properties holds when $V_G = 0$ V. The C-f and θ-f measurement for sample B show an anomalous behavior. The similar results can be obtained in direct magnetization measurement of sample B by using superconducting quantum interference device. From this experiment, we found that the saturation magnetic moment is continuously increased (decreased) by applying positive (negative) gate voltage. These results strongly suggest that drastic change in magnetism in sample B is caused by the modulation of the effective ferromagnetic Co thickness due to the voltage-driven mobile oxygen ions in HfO_2 [6].

4. Conclusions

We have shown that the mechanisms of the EF effect on magnetism in the surface-oxidized Co depends on the quality of gate dielectric oxide layer.

Acknowledgements

The authors thank Prof. M. Kohda, Prof. S. Ono, Prof. Y. Kozuka, and Prof. M. Kawasaki for the useful discussion and the technical help. This work was partly supported by Grants-in-Aid for Scientific Research (S) and Specially Promoted Research (Grant Nos. 25220604 and 15H05702) from JSPS, and Spintronics Research Network of Japan. A part of the work was performed using facilities at the Cryogenic Research Center, the University of Tokyo.

References

[1] F. Matsukura *et al.*, Nat. Nanotechnol. **10** (2015) 209.

[2] K. Nakamura *et al.*, Phys. Rev. Lett. **102** (2009) 187201.

[3] M. Tsujikawa *et al.*, Phys. Rev. Lett. **102** (2009) 247203.

[4] C. Bi *et al.*, Phys. Rev. Lett. **113** (2014) 267202.

[5] T. Hirai *et al.*, Appl. Phys. Express **9** (2016) 063007.

[6] T. Hirai *et al.*, Appl. Phys. Lett. **112** (2018) 122408.

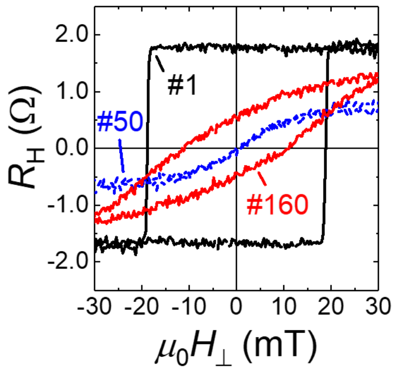

Fig. 2: The anomalous Hall loops for sample B (For the cycle number, see Fig. 1).