Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp567-568

K-8-03

Current-induced switching in paramagnetic-CoGa buffer / $L1_0$ MnGa / MgO structure with a perpendicular magnetic anisotropy

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Abstract

Current-induced magnetization switching is reported in ultrathin films of Mn-based ordered alloy. The paramagnetic CoGa-buffered and MgO-capped 2-nm-thick $L1_0$ MnGa films clearly showed a perpendicular magnetic anisotropy, measured by the micron-sized Hall devices. The devices also showed that anomalous Hall hysteresis curves as a function of the in-plane electrical current. The current-induced switching phase diagram, *i.e.* the switching current *vs.* longitudinal in-plane magnetic field, indicated that the observed current-induced switching stemmed from the spin-orbit torque due to the spin-Hall effect for CoGa with the positive spin-Hall angle.

1. Introduction

Tetragonal magnetic ordered alloys with a high magnetic anisotropy have attracted much attention for high-density nonvolatile memory applications. Among many of such materials, tetragonal Heusler-like Mn-based alloys and its derivatives, such as MnGa, Mn_3Ga, and Mn_3Ge have extensively studied as a free layer for perpendicular magnetic tunnel junctions (p-MTJs). This is because those Mn-based materials have very low net-magnetic moments owing to ferrimagnetism, high uniaxial magnetic anisotropy, low Gilbert damping, and high spin polarization [1-10].

Recently we have discovered the low-temperature growth method of 1-3-nm-thick MnGa films with well-chemically ordered crystal structure and *c*-axis orientation using a paramagnetic CoGa buffer layer [11]. Using this method, we have developed the ultrathin MnGa/MgO p-MTJs, in which a huge tunnel magnetoresistance (TMR) effect was predicted owing to the epitaxial strain effect on its band structure [12]. Subsequently we have also demonstrated the in-plane current induced spin-orbit torque (SOT) switching [13-14] in CoGa/MnGa/Pt films with a perpendicular magnetic anisotropy (PMA) [15]. Independently, the other group have also reported the current-induced switching in GaAs substrate / MnGa / heavy metal structure [16]. These layered-structures with the heavy metal capping layer are useful for investigation of physics behind SOT, whereas it cannot be applied to three terminal p-MTJs devices for practical memories [17-18].

In this study, we report the observation of current-induced magnetization switching in ultrathin MnGa films even in the structure of CoGa/MnGa/MgO without a heavy metal capping layer [19].

2. Experimental Methods

The films were fabricated using the ultra-high vacuum magnetron sputtering, and the stacking structure was (100) MgO single crystal substrate / MgO (10) / $Co_{55}Ga_{45}$ (20) / $Mn_{59}Ga_{41}$ (2) / MgO (2) / Ta (2) (thickness is in nm) [Fig. 1(a)]. The film structure was characterized by X-ray diffraction. The magnetic properties were measured by a polar magneto-optical Kerr effect and vibrating sample magnetometer. The film was patterned into the Hall devices with 6-μm-width and 30-μm-length using the conventional ultraviolet photo-lithography and Ar ion milling [15]. The anomalous Hall resistance R_H was measured using the four terminal method with dc or pulse current. In this measurement, the out-of-plane magnetic field H_z or the longitudinal in-plane magnetic field H_y was applied [Fig. 1(a)]. All the measurements were performed at room temperature.

3. Experimental Results and Discussion

The R_H as a function of H_z is shown in Fig. 1(b), which was measured with the dc current I_{dc} of +1 mA. The rectangular hysteresis is clearly observed and the coercively $\mu_0 H_c$ is about 150 mT. The effective PMA field H_k^{eff} was ~ 2.6 T evaluated from the R_H-H_y curve (not shown here). Saturation magnetization was 350 ± 50 kA/m, so that the effective PMA constant thickness product $K_u^{eff}\,t$ was ~ 0.5 mJ/m^2.

Figures 2(a), 2(b), and 2(c) show R_H as a function of the pulse current I_p with $\mu_0 H_y$ of 100, 0, and -100 mT, respectively. The pulse duration for the current pulse was 100 μs in this measurement. The clear current-induced switching are observed at I_p ~ 20 mA. Magnetization process is reversed with polarity of H_y, as seen in the figures. In addition, the R_H values show no remarkable change in case of $\mu_0 H_y$ = 0 mT. These behaviors are accord with current-induced SOT switching observed previously in substrate/Pt/Co/Al-O films with PMA [14]. The hysteresis loops also show the parabolic change, which indicate the presence of the Joule heating. The magnetic field stemming from the electric current, the so-called Oersted's field, is estimated to be about 4.5 mT at I_p ~ 22 mA, which may have negligible influences.

Figure 3 shows the magnetization switching phase diagram, *i.e.*, the switching current I_c *vs.* H_y. When H_y is positive and large enough, the stable magnetization direction is downward (upward) for positive (negative) I_p over $|I_c|$. On the other hand, when H_y is negative and large enough, the stable magnetization direction is upward (downward) for positive (negative) I_p over $|I_c|$. This symmetry of the phase diagram is the same as that observed in substrate/Pt/Co/Al-O films with PMA [14]. This suggests that the sign of the spin-Hall angle for CoGa is positive, being the same sign as that for Pt.

The switching current density J_c in the experiment is estimated to be 2×10^{11} A/m^2 at $\mu_0 H_y$ =200 mT when the current is assumed to flow only in the CoGa layer since the resistivity of MnGa and CoGa are comparable [15]. This experimental J_c is comparable to that observed in Pt/Co/Al-O films even though $K_u^{eff}t$ in our sample is by a factor of about 5 larger. This may be partially attributed to the effect of the Joule heating and non-uniform magnetization switching. In addition, the result suggests that the spin-Hall angle of the paramagnetic CoGa is non-negligibly large. This could originate from a high resistivity of CoGa as well as the relatively large spin-orbit interaction of Ga 4*p* orbitals, which is comparable to that of Pd 4*d* orbitals [19], though the effect of paramagnetic fluctuation of magnetic moment for CoGa on the spin-Hall effect is not yet clear. These issues are left to future studies.

4. Summary

Current-induced magnetization switching was studied in the CoGa-buffered and MgO-capped 2-nm-thick $L1_0$ MnGa films with PMA. The micron-sized Hall devices clearly showed the magnetization switching as a function of the in-plane electrical current only at the presence of the longitudinal magnetic field. The switching phase diagram indicated that the observed current-induced magnetization switching stemming from SOT. This study demonstrated that SOT-switching is possible in CoGa/MnGa/MgO which could serve as the bottom layer for three terminal p-MTJs for the memory scaled below 20 nm technology node.

Acknowledgements

This work is partially supported by Grant-in-Aid for Scientific research (No. 16H03846 and No. 17K14103), the ImPACT program, Sasagawa foundation. The authors thank to Y. Kondo for technical assistance.

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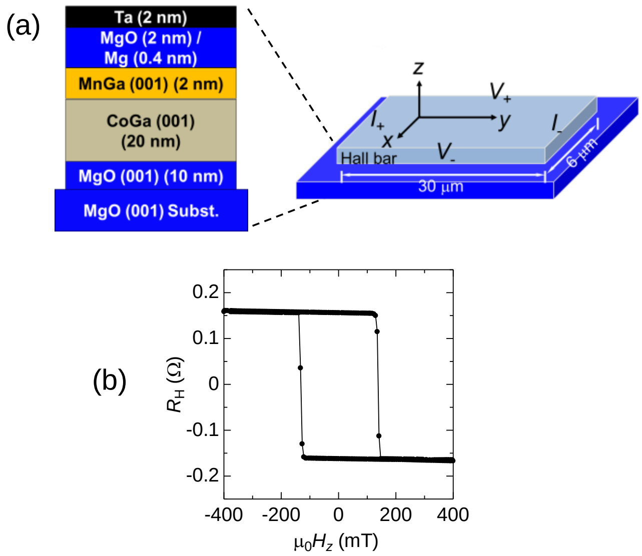

Fig. 1 (a) Cartoon of a film stacking structure and measurement geometry. (b) The anomalous Hall resistance R_H for the Hall bar measured at I_{dc} = + 1 mA.

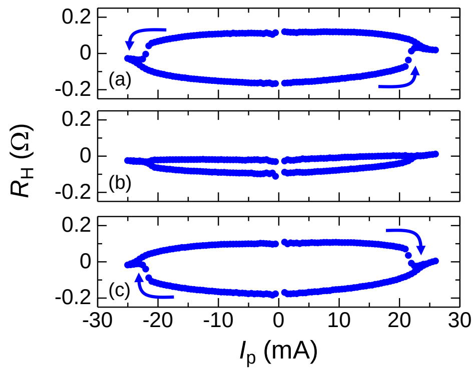

Fig. 2 The anomalous Hall resistance R_H *vs.* the pulse current I_p with (a) $\mu_0 H_y$ = 100, (b) 0, and (c) -100 mT. The data points near I_p = 0 mA were removed. A pulse duration was 100 μs.

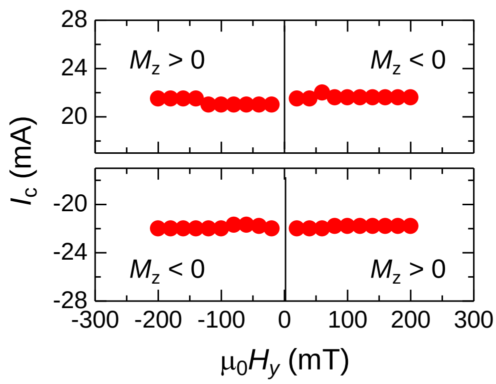

Fig. 3 The current-induced switching phase diagram of the switching current I_p *vs.* H_y.