Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp175-176

C-6-04(Late News)

Current-induced magnetization switching in a MnGa/Pt film

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Abstract

Current-induced magnetization switching is reported, for the first time, in ordered Mn-based alloys ultrathin films. The Pt-capped 2-nm-thick 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 in-plane electrical current only at the presence of the external magnetic field parallel to the current direction. The phase diagram of the swithing current vs longitudinal magnetic field indicated that the observed current-induced magnetization switching stemmed from the spin-orbit torque.

1. Introduction

Tetragonal magnetic ordered alloys with high magnetic anisotropy have attracted much attentions for high-density storage and memory applications. Among many of such materials, tetragonal Heusler-like Mn-based alloys and its derivatives, such as MnGa and Mn_3Ge have extensively studied for application of spintronic memory and logic applications based on magnetic tunnel junctions (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 [1-4]. Quite 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 [5]. This discovery enabled us to develop the ultrathin MnGa/MgO perpendicular MTJs, in which a huge tunnel magnetoresistance (TMR) effect was predicated owing to the epitaxial strain effect on its band structure [6].

There are still many issues for practical applications using Mn-based alloys [1]. One of the issues is a current-induced spin-orbit torque (SOT) switching of magnetization in ultrathin films of Mn-based alloy with large perpendicular magnetic anisotropy (PMA). There are many studies on SOT in ultrathin films with an interfacial PMA, such as heavy metal layer / magnetic layer / oxide layer, where SOT is induced by the in-plane electrical current via the spin-Hall or the Rashba effect [7,8]. It is also demanded to clarify SOT in the films with a bulk PMA, such as the above-mentioned ordered magnetic alloys and amorphous rare-earth transition metals magnets [9,10], because of examination of potential applications into magnetoresistive random access memory (MRAM) scaled below 20 nm technology node. Quite recently Meng *et al.* studied the anomalous Hall effect in MnGa / heavy metals (Pt and Ta) and discuss the influence of spin-Hall effect [11]. Nevertheless, no current-induced magnetization switching has been reported. Here we report, for the first time, the current-induced magnetization switching in ultrathin MnGa films with PMA.

2. Experimental Procedure

The films were fabricated using the ultra-high vacuum magnetron sputtering, and the stacking structure was (100) MgO single crystal substrate / CoGa (15) / MnGa (2) / Pt (2) (thickness is in nm), where CoGa served as the buffer layer [5]. The film structure was measured by X-ray diffraction and the magnetic properties were characterized by a polar magneto-optical Kerr effect. 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. The Hall resistance R_H was measured with the standard DC four terminal method with applying the longitudinal magnetic field H_L or perpendicular magnetic field H [Fig. 1(a)]. All the measurements were performed at room temperature.

3. Experimental Results

The R_H as a function of H is shown in Fig. 1(b), which was measured with the current I of 1 mA. This $R_H - H$ loops corresponds the magnetization $M - H$ loop for the MnGa layer. The rectangular hysteresis is clearly observed and the coercivity H_C is about 500 Oe, even though MnGa is very thin.

Figure 2(a) and 2(b) shows R_H as a function of I with H_L of -500 and 500 Oe, respectively. The clear current-induced switching are observed at $I \sim \pm 10$ mA. Magnetization process is reversed with polarity of H_L, as seen in the figures. In addition, the R_H values show no remarkable change in case of $H_L = 0$ Oe (not shown here). These behaviors are accord with current-induced switching observed in other films with PMA [10,12]. The hysteresis loops also show the parabolic change, which could be due to the Joule heating.

Figure 3 shows the magnetization switching phase diagram, *i.e.*, the switching current I_S *vs.* H_L. The absolute values of I_S decreases with increasing H_L. The phase diagram is slightly asymmetric with respect to the polarity of I, which is similar to that observed in Pt/Co/Al-O films [12]. It should be noted that the magnetic field stemming from the electric current, the so-called Oersted's field, is estimated to be about 20 Oe at $I = 10$ mA, which may have negligible influences.

4. Discussion

In case of uniform rotation of magnetization without thermal fluctuation, the switching current J_S for current-induced SOT magnetization switching for perpendicular magnetization is expressed as [13],

$$J_S = \frac{2e}{\hbar}\frac{M_S d_F}{\vartheta_S}\left(\frac{H_k^{eff}}{2} - \frac{H_L}{\sqrt{2}}\right), \qquad (1)$$

where e and $\hbar$ are the electron charge and the Dirac constant, respectively. M_S, H_k^{eff}, and d_F are the saturation magnetization, the effective PMA field, and thickness of magnetic layer, respectively. In this model, the current I flows only into the heavy metal layer with the spin-Hall angle θ_S. The phase diagram is qualitatively consistent with eq. (1), namely I_s can be reduced with increasing H_L. The switching current density J_S in the experiment is estimated to be 83 MA/cm^2 when the current of 10 mA is assumed to flow only in the Pt layer. The actual value of J_S may be still of the order of 10 MA/cm^2 because the resistivities for MnGa and CoGa are roughly several times larger than that for Pt [14,15]. This experimental J_S is much smaller than that predicted by eq. (1) with the relevant material parameters. This could be explained by the influences of non-uniform magnetization process, the thermal fluctuation of magnetization, and the Joule heating in the devices [12]. Those will be addressed elsewhere.

4. Summary

Current-induced magnetization switching was studied in the Pt-capped 2-nm-thick 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 Mn-based magnets with PMA with moderate electrical current density.

Acknowledgements

This work is partially supported by Grant-in-Aid for Scientific research for Basic Research B (No. 16H03846) and the ImPACT program. Y.S. thanks to the GP Spin program. The authors thank to T. Miyazaki for valuable comments.

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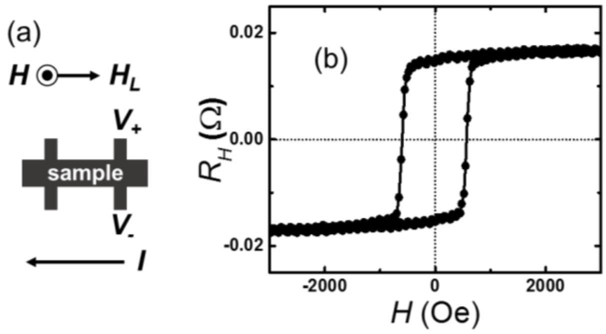

Fig. 1 (a) Cartoon of measurement geometry with applying the magnetic field perpendicular to the plane H and in the plane H_L. (b) The anomalous Hall resistance of the MnGa/Pt Hall devices measured at I = + 1 mA and H_L = 0 Oe.

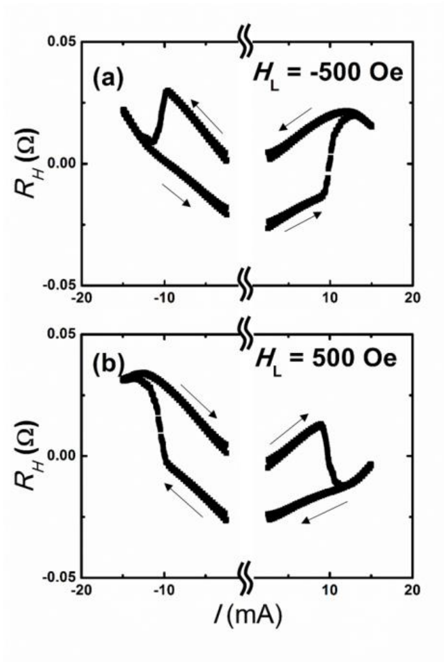

Fig. 2 The anomalous Hall resistance of the MnGa/Pt Hall devices *vs.* I with (a) H_L = -500 Oe and (b) H_L = +500 Oe. The data points near I = 0 mA are removed.

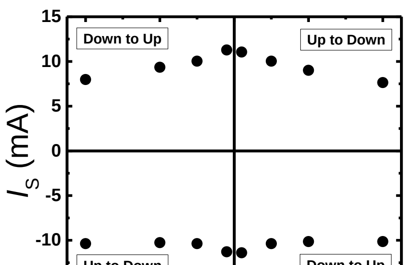

Fig. 3 The phase diagram of switching current I_S *vs.* H_L with H = 0 Oe.