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Spin-orbit-torque induced magnetization switching for an ultra-thin MnGa/Co_2MnSi bilayer

○Kohey Jono[1], Fumiaki Shimohashi[1], Michihiko Yamanouchi[2], and Tetsuya Uemura[1]

[1]Grad. School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan
[2]Research Institute for Electronic Science, Hokkaido University, Sapporo 001-0020, Japan
E-mail: jono_k@eis.hokudai.ac.jp

Abstract

We investigated the spin-orbit-torque (SOT) induced magnetization switching and SOT efficiency for a MnGa single layer and a MnGa/Co_2MnSi(CMS) bilayer. The magnetization and polar Kerr signal measurements showed that ultrathin MnGa and CMS were antiferromagnetically coupled each other with clear perpendicular magnetization. The SOT-induced magnetization switching was observed for both MnGa/CMS/Ta and MnGa/Ta stacks, and the switching current was reduced by half in the MnGa/CMS/Ta. Moreover, it was found by examining the interaction between domain walls and the SOT that the effective magnetic field originating from the SOT was enhanced by ~5 times in the MnGa/CMS/Ta than in the MnGa/Ta. These results indicate that a MnGa/CMS bilayer structure is effective in enhancing the efficiency of generating SOT.

1. Introduction

A bilayer consisting of MnGa and Co-based Heusler alloy (Co_2YZ, where Y is usually a transition metal and Z is a main group element) is expected to be a promising ferromagnetic electrode for a perpendicular magnetic tunnel junction (p-MTJ) with high tunnel magnetoresistance and high thermal stability due to the half-metallic nature of Co-based Heusler alloys and the large perpendicular magnetic anisotropy (PMA) of MnGa. The previous studies have proved that MnGa and some of Co_2YZ are antiferromagnetically coupled each other [1,2]. Moreover a p-MTJ with MnGa/Co_2MnSi(CMS) electrodes has also been reported [3]. However, the thickness of MnGa in these structures was larger than 10 nm, which is not applicable to the spin-transfer-torque induced or spin-orbit-torque (SOT) induced magnetization switching. There has been several reports on the SOT-induced magnetization switching for an ultrathin MnGa single layer [4-7], while those for a MnGa/Co_2YZ is very limited: MnGa/Co_2FeAl [4] and MnGa/CMS. Thus, the effect of Co_2YZ on the SOT characteristics has not been fully understood. In this study we quantitatively investigated the saturation magnetization, SOT-switching characteristics and SOT-induced effective magnetic field for MnGa/Ta and MnGa/CMS/Ta stacks grown on the same substrate to clarify the effect of CMS layer on the magnetic properties and SOT characteristics for an ultra-thin MnGa/CMS bilayer.

2. Experimental Methods

A layer structure consisting of (from the substrate side) MgO buffer (10)/NiAl buffer (5)/ MnGa (2 or 3)/CMS (1)/Ta (5)/MgO cap (2) was deposited on an MgO(001) single-crystalline substrate (numbers in parentheses are nominal thicknesses in nanometers). The CMS layer was deposited on the half area of the MnGa layer by using a slide shutter [Fig. 1(a)]. The layer structure was processed into Hall devices with a 5-μm-wide channel by photolithography and Ar ion milling to investigate the SOT-switching characteristics. We also evaluated the effective magnetic field, $\mu_0 H_{\mathrm{eff}}$, originating from the SOT in the MnGa(3)/CMS/Ta and MnGa(3)/Ta devices by examining the interaction between domain walls and the SOT [7,8].

3. Results and Discussion

Figure 1(b) shows magnetic hysteresis loops for a MnGa(2) with and without CMS obtained by magneto-optical Kerr effect (MOKE) measurement at room temperature. Both curves show clear PMA characteristics even for a 2-nm-thick ultrathin MnGa with CMS. The magnetization measurements showed the reduction of the saturation magnetization in the MnGa(2 or 3)/CMS bilayer compared with MnGa(2 or 3) single layer (*not shown*), indicating that the MnGa and CMS are antiferromagnetically coupled each other. This result is consistent with the previous studies [1,2].

Figure 2 shows current-induced magnetization switching for (a) MnGa(2)/Ta and (b) MnGa(2)/CMS/Ta under in-plane field $\mu_0 H_x$ = 0.05 T. We observed clear magnetization switching with pulse current I_P with the duration of 100 μs for both devices. Taking the directions of I_P and $\mu_0 H_x$ into consideration, the observed magnetization switching is consistent with those expected from the switching by the SOT originating from the spin Hall effect in the Ta layer. Interestingly, the switching current for the MnGa/CMS/Ta is approximately half of that for the MnGa/Ta, indicating that combining CMS with MnGa is effective in reducing the switching current due to the antiferromagnetic exchange coupling between CMS and MnGa.

In order to evaluate the effect of CMS on the strength of SOT-induced $\mu_0 H_{\mathrm{eff}}$, we measured the shift of magnetic hysteresis loops for a MnGa(3) with and without CMS. Figure 3(a) shows normalized anomalous Hall resistance R_{AHE} for MnGa(3)/CMS with dc current $I = \pm 12$ mA as a function of out-of-plane field $\mu_0 H_z$ under in-plane field $\mu_0 H_x$ = 0.45 T. When positive (negative) I was applied to the channel, the center of the hysteresis loop was shifted in the negative (positive) $\mu_0 H_z$-axis direction. The shift amount gives $\mu_0 H_{eff}$, because the shift is caused by the SOT acting on the magnetization in the DW [8]. The values of $\mu_0 H_{eff}$ are plotted as a function of current I in Fig. 3(b). They varied proportionally to I and the sign of the linear slope was reversed in accordance with the polarity of $\mu_0 H_x$. Figure 3(c) shows comparison of $\mu_0 H_{eff}$ as a function of $\mu_0 H_x$ between MnGa/Ta device and MnGa/CMS/Ta device. Importantly, the value of $\mu_0 H_{eff}$ was ~5 times larger for the MnGa/CMS/Ta device than that for the MnGa/Ta device, indicating that MnGa/CMS bilayer structure is effective in enhancing the efficiency of generating SOT.

4. Summary

We experimentally found that MnGa and CMS were antiferromagnetically coupled each other with clear perpendicular magnetic anisotropy. The current needed for the SOT-induced magnetization switching was reduced by half and the effective SOT field was enhanced by ~5 times in a MnGa/CMS bilayer than in a MnGa single layer. These results indicate that a MnGa/CMS bilayer structure is effective in enhancing the efficiency of generating SOT. The reduction of magnetization by the antiferromagnetic coupling can contribute to the enhancement.

Acknowledgements

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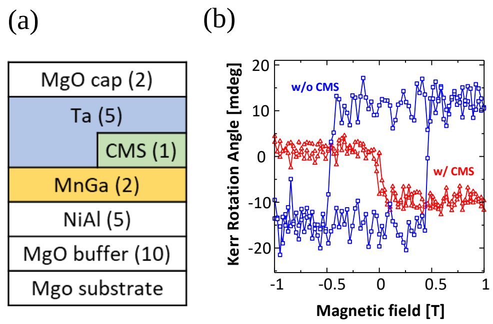

Fig. 1. (a) Stack structure of the fabricated film. (b)MOKE signals for MnGa(2)/CMS and MnGa(2) as a function of out-of-plane magnetic field.

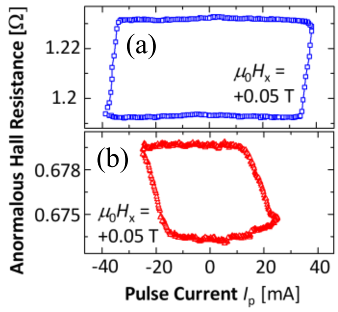

Fig. 2. Anomalous Hall resistance of (a) MnGa(2) and (b) MnGa(2)/CMS as a function of pulse current I_p with the duration of 100 μs under $\mu_0 H_x$ = + 0.05 T.

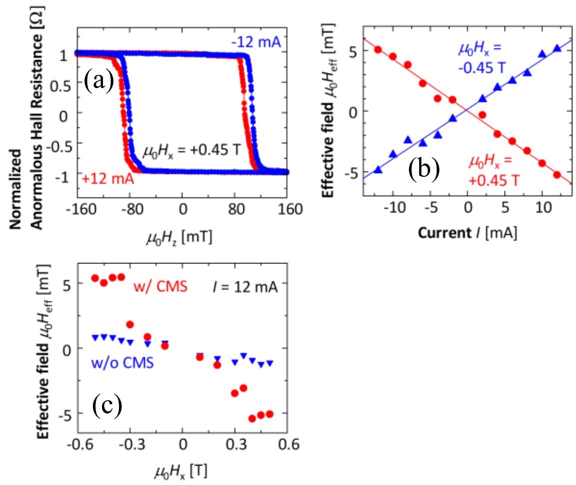

Fig. 3. (a) Normalized anomalous Hall resistance for a MnGa(3)/CMS sample with dc current I = ±12 mA and in-plane field $\mu_0 H_x$ = 0.45 T. (b) Effective field $\mu_0 H_{eff}$ for a MnGa(3)/CMS sample as a function of current I. (c) Comparison of $\mu_0 H_{eff}$ as a function of $\mu_0 H_x$ for MnGa(3) and MnGa(3)/CMS samples.