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Influence of Stray Field on Magnetization Switching Induced by Spin-Orbit Torque

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In a vertical domain wall motion memory with artificial ferromagnets, magnetization switching induced by spinorbit torque (SOT) is employed for the data-writing method. This data-writing process may suffer from stray fields from the reference layer; however, this effect has been rarely addressed so far. In this study, we investigated the relationship between the critical current density required for SOT-induced magnetization switching and the stray field by varying the ferromagnetic layer thickness of synthetic antiferromagnetic reference layers in nanopillars with diameters of 300 nm and 200 nm. The results reveal that the critical current density is little affected by changes in the stray field in our system.

Keywords: domain wall motion memory, stray field, hysteresis, spin-orbit torque, thickness dependence

1. Introduction

Domain wall (DW) motion in magnetic nanowires has attracted considerable interest due to its non-volatility and potential for high-density integration¹⁾⁻³⁾. In the DW motion memory, logic bits are stored in magnetic domains and separated by DWs. By injecting electric currents, these logic bits can be moved to desired storage position due to the motion of the DWs^{4),5)}.

For practical applications, high thermal stability is crucial to retain the magnetization direction against external disturbance considering the data security. The thermal stability factor Δ of a magnetic memory device can be described by $\Delta = E_b/(k_BT)$, where E_b , k_B , and Tare the energy barrier, the Boltzmann constant, and the temperature. On the other hand, a low critical current (J_c) to drive the DW motion is necessary to minimize electricity consumption and heat generation. However, there exists a dilemma between maintaining the thermal stability of data and achieving the low operation current. Enhancing E_b improves thermal stability but simultaneously increases the critical current density⁶.

To address this issue, a novel vertical DW motion memory with artificial ferromagnets exhibiting perpendicular magnetic anisotropy (PMA) was designed in our previous works^{7),8)}. In this memory cell, data bits are written into the bottommost ferromagnetic layer by injecting in-plane currents through the heavy metal bottom electrode to induce spin-orbit torque (SOT)⁹⁾⁻¹³⁾. Then, the bits can be shifted to upper layers by spintransfer torque (STT) through out-of-plane pulse injection¹⁴⁾⁻¹⁶⁾. Micromagnetic simulations have shown that by tuning the properties of each layer, it is possible to achieve both a low critical current density ($J_c < 10^{11}$ A m⁻²) and high thermal stability ($\Delta > 60$)⁸⁾. However, in this structure, the stray field from the other layers may affect the memory operation in datawriting and shift processes¹⁷⁾. In this study, we investigated the influence of stray field on the SOTinduced magnetization switching for the writing process in nanopillars with PMA.

2. Experimental results

2.1 Device fabrication

Multilayers of Ta(5) / Pt(10) / Co(1.4) / Cu(3) / Co(0.8) / Pt(0.8) / Co(0.8) / Ru(0.75) / Co(0.8) / Pt(0.8) / Co(t_{Co} : 0.4-1.0) / Pt(3) were deposited on thermally oxidized Si substrate using sputtering as shown in Fig. 1(a). The numbers in parentheses are the thickness of each layer in nanometers. The bottom 10-nm-thick Pt layer was utilized for the bottom electrode to induce SOT. The 3nm-thick Cu layer is a spacer layer between free layer and synthetic antiferromagnet (SAF) to read out the information of magnetization configuration through the giant magnetoresistance (GMR) effect. SAF structure was used as a reference layer of memory cells to reduce



Fig. 1 (a) Schematic illustration of multilayer structure. (b) Polar-Kerr hysteresis loop of sample with $t_{\rm Co} = 0.72$ nm. Thick and thin arrows represent magnetization of SAF layer and the free layer, respectively.

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Fig. 2 (a) Schematic of experimental setup for GMR and AHE measurements. (b) Pillar resistance R_{pillar} and (c) Hall resistance R_{AHE} as a function of out-of-plane magnetic field, respectively, in 300 nm device.

the stray field¹⁸⁾, which may suppress the efficiency of SOT-induced magnetization switching. In SAF structure, the net magnetization in the antiparallel magnetization configuration depends on the thickness ratio of two ferromagnetic layers. Therefore, the wedge-shaped Co layer was made to vary the strength of stray field. Figure 1(b) shows the polar-Kerr hysteresis loop of the sample with $t_{\rm Co} = 0.72$ nm, indicating that the magnetization of the free layer switches in smaller magnetic field than that of the SAF layer.

This film was fabricated into nanopillars with 300 nm and 200 nm diameters by electron beam lithography and Ar ion etching. The Pt bottom layer was patterned into a 1-µm-wide stripe, and the rest of the layers were etched to form a nanopillar on the Pt bottom layer. The etchings depth was monitored by in-situ secondary ion mass spectroscopy for the endpoint detection. The hysteresis of the devices was measured by GMR effect and anomalous Hall effect (AHE) by sweeping an out-of-plane magnetic field using the experimental setup shown in Fig. 2(a). A 0.5 mA DC current was applied by a current source, and the pillar resistance R_{pillar} and Hall resistance R_{AHE} were evaluated from corresponding voltages.

2.2 Hysteresis measurements

Minor hysteresis loops measured by a 300 nm pillar with $t_{Co} = 0.91$ nm are shown in Figs. 2(b) and 2(c). The magnetization configurations of each state are represented by arrows in the figure. Square hysteresis with sharp resistance changes indicate that the free layer has a perpendicular easy axis with sufficiently large PMA. In the AHE measurements, the switching signal appears at a magnetic field almost identical to that in the GMR measurements, suggesting that this resistance change also arises from the switching of the free layer.

It should be noted that in the antiparallel magnetization configuration of the SAF structure, the magnetization of the Co/Pt/Co layer with a larger total magnetic moment should be oriented in the magnetic field direction because it is more stable to reduce the Zeeman energy. In our sample, the thickness of the lower Co/Pt/Co layer is fixed. Thus, in case of small t_{Co} , the magnetic moment of the SAF is dominated by the lower Co/Pt/Co layer and vice versa. This means that there exists a Co thickness such that the magnetization of the upper and lower Co/Pt/Co layers exactly cancels out. For the devices on two sides of this thickness, their magnetizations of SAFs should orient in opposite directions. This difference can be examined by GMR curves. Figures 3(a) and 3(b) show the hysteresis of 300 nm devices with $t_{Co} = 0.55$ nm and 0.58 nm. Two hysteresis loops show opposite polarities that the low-(high-)resistance states were obtained for the device with $t_{\rm Co} = 0.55$ nm (0.58 nm) at large positive field, respectively. Since the free layer magnetization is now oriented in the +z direction, the magnetization configuration of the SAF structure can be deduced from the resistance states of R_{pillar} as represented by arrows in the figure. The results of Figs. 3(a) and 3(b) reveal that the Co thickness at which the antiparallel magnetization configuration of the SAF structure is inverted is approximately between 0.55 and 0.58 nm. This thickness is smaller than the expected thickness of $t_{Co} = 0.8$ nm from the symmetry of the film structure. This discrepancy can be attributed to the contribution of the magnetization induced in the top Pt capping layer through the proximity $effect^{19),20)}$.

We then measured the minor hysteresis loops of devices with various t_{C_0} to estimate the hysteresis shift, which is the shift of the center field of the free layer



Fig. 3 (a) (b) Out-of-plane magnetic field dependence of R_{pillar} measured using 300-nm devices with (a) $t_{\text{Co}} = 0.55$ nm and (b) $t_{\text{Co}} = 0.58$ nm, respectively. (c) Co thickness dependence of hysteresis loop shift.

hysteresis loops. For each device, 10 measurement cycles were performed to evaluate the average value of switching fields to minimize the effect of thermal fluctuation. The magnetizations of the SAF structure were set to the same configuration as represented in Fig. 3(b) before the measurements. Figure 3(c) shows the evaluated hysteresis loop shift as a function of t_{Co} . We expected the hysteresis loop shift to vary monotonically with respect to the tco. However, in 300 nm and 200 nm devices, the hysteresis loop shift does not show a clear trend with respect to t_{Co} and is positive in most devices. This may be because the stray field is more sensitive to the microfabrication imperfection than to the variation of the Co thickness in SAF structure. Hereafter, we assume that this hysteresis loop shift corresponds to the stray field to the free layer 21 .

2.3 SOT-induced magnetization switching

Next, we investigated the influence of stray field on SOT-induced magnetization switching. In the experiments, in-plane current pulses with 20 ms pulse duration were injected to the bottom Pt electrode to generate spin current originating from the spin-Hall effect. AHE resistance which is proportional to the outof-plane component of the magnetization was measured under a 0.5 mA DC current. An in-plane magnetic field is applied to break the mirror symmetry²²⁾. In all measurements, the magnetization configurations in SAF structure were also set to be the same configuration as represented in Fig. 3(b). Figure 4(a) shows the SOT switching loops of a 300 nm pillar with $t_{Co} = 0.91$ nm, where ΔR_{AHE} is calculated by subtracting the R_{AHE} offset. The change in ΔR_{AHE} reflects the complete switching of the free layer magnetization as shown in Fig. 2(c). When the direction of the in-plane magnetic field is reversed, the loop polarity also changes, which is a distinct feature of SOT-induced switching.

The Co thickness dependence of the critical current of SOT switching was studied with the application of a +50 mT in-plane magnetic field. To facilitate comparisons between different devices, we define J_c as the current density when the change in resistance is 20% of the full resistance change in the hysteresis measured by AHE, because several samples exhibited a reduced ΔR_{AHE} in the SOT switching loop compared to that observed in the hysteresis. The positive critical current density J_c and the absolute value of the negative critical current density $|-J_c|$ are plotted as a function of t_{Co} in Figs. 4(b) and 4(c), where the J_c was evaluated from the average value from 10 repeated measurements. Then the SOT loop shift was evaluated from $(J_c - |-J_c|)/2$.

To investigate the influence of the stray field on the SOT-induced magnetization switching, we plotted the relationship between the SOT loop shifts and hysteresis loop shifts in Fig. 4(d). From this result, we find little correlation between them for both the 300 nm and 200 nm devices, despite there is a larger deviation in the 200 nm devices compared to the 300 nm devices due to microfabrication imperfections. This implies that the response of the critical current density to changes in the stray field is insensitive in our system. A plausible explanation is that, unlike the situation with the direct application of an external magnetic field, the stray field from the reference layer in the nanopillar may exhibit an inhomogeneous distribution across the free layer. This leads to the experimental results differing from our expectation that the SOT loop shifts and hysteresis loop shifts would show a clearer correlation.



Fig. 4 (a) SOT-induced magnetization switching under in-plane magnetic field of ± 50 mT using 300-nm device with $t_{\rm Co} = 0.91$ nm. (b) (c) Co thickness dependence of $J_{\rm c}$ and $|-J_{\rm c}|$ in diameter of (b) 300-nm and (c) 200-nm nanopillars. (d) Relationship between hysteresis loop shift and SOT loop shift.

3. Conclusion

We investigated the critical current density of SOTinduced free-layer magnetization switching in nanopillars of 300 nm and 200 nm diameters, with reference SAF layers of different Co thickness. Within the range of stray fields observed in our hysteresis measurements, we found that there is little correlation between the critical current density and the stray field.

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