ISSN (Print) 1598-5385
ISSN (Online) 2233-6648
≪연구논문≫ Journal of the Korean Magnetics Society 34(5), 219-223 (2024) https://doi.org/10.4283/JKMS.2024.34.5.219

Study on Spin-orbit Torque-induced Magnetization Switching in a Ferrimagnetic GdFeCo/Pt Using Complementary Electric and Optical Measurements

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(Received 14 October 2024, Received in final form 28 October 2024, Accepted 29 October, 2024)

We carried out spin-orbit torque (SOT) induced magnetization switching experiments in a ferrimagnetic GdFeCo/Pt with perpendicular magnetic anisotropy. To clearly understand the magnetization switching in the GdFeCo/Pt Hall bar structure, we investigated the magnetization switching phenomena via electric and optical techniques, such as the anomalous Hall measurement and simultaneously the magneto-optical Kerr effect imaging. It is found that the SOT-induced switching is accomplished via the local nucleation of domains and domain wall motions. It is also observed that the anomalous Hall signal due to spin-orbit torque was slightly smaller compared to that of the magnetic field-induced reversal. We confirm that the smaller signal is due to the incomplete magnetization switching in the Hall bar.

Keywords : spin-orbit torque switching, magneto-optical kerr effect, anomalous hall effect

상호보완적인 전기적 광학적 측정을 통한 준강자성 GdFeCo/Pt에서의 스핀-궤도 토크에 의한 자화 스위칭 연구

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(2024년 10월 14일 받음, 2024년 10월 28일 최종수정본 받음, 2024년 10월 29일 게재확정)

수직 자기 이방성을 가진 GdFeCo/Pt 페리자성체에서 스핀-궤도 토크에 의한 자화 반전 실험을 수행했다. GdFeCo/Pt 홀 바 구조에서 스핀-궤도 토크에 의한 자화 반전 메커니즘을 명확히 이해하기 위해, 전기적 및 광학적 기법, 예를 들어 비정상 홀 측정 및 자기 광학 커 효과 이미징을 동시에 사용하여 자화 반전 현상을 연구했다. 실험 결과, 스핀-궤도 토크 자화 반전은 국소적인 자구 생성과 뒤따르는 자구벽 움직임을 통해 전체 소자에서의 자화 반전이 이루어짐을 확인했다. 또한 외부 자기장에 의한 자화 반전을 나타내는 비정상 홀 저항에 비해 스핀-궤도 토크에 자화 반전을 나타내는 비정상 홀 저항이 약간 작다는 것을 관찰했다. 이러한 더 작은 신호는 홀 바 내에서의 줄어든 전류밀도에 의한 불완전한 자화 반전에 기인함을 확인했다.

주제어 : 스핀-궤도 토크 스위칭, 자기 광학 커 현상, 비정상 홀 효과

I. Introduction

Spintronic devices have garnered significant attention in the development of magnetic memory and logic devices [1-5]. In these magnetic devices, controlling magnetization corresponds to writing information, making electrical control of magnetization crucial. Unlike spin-transfer torque (STT), which uses spin currents which have passed a magnetic pinned layer to reverse magnetization in a magnetic free layer [6,7], the combination of a ferromagnetic layer and a heavy metal layer with strong spin-orbit coupling can generate an efficient spin torque via the current flowing in the heavy metal layer. This is known as spin-orbit torque (SOT), where

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the spin Hall effect in the heavy metal layer induces spin polarization, and the spin-polarized current injected into the ferromagnetic layer exerts a torque on the magnetization [8-10]. One component of SOT is the damping-like torque, which, when combined with an in-plane magnetic field along the current direction, can selectively align perpendicular magnetization. As a result, SOT-driven switching in materials with perpendicular magnetic anisotropy (PMA) has been a main focus in the field of spintronics over the past decade.

Magnetization switching driven by SOT has primarily been investigated through electrical measurements using the anomalous Hall effect (AHE) [1-5,11-13]. In Hall-bar devices, the anomalous Hall voltage is typically proportional to the magnetization at the Hall cross, making AHE measurements advantageous for easily monitoring the magnetization behavior in microscale devices. However, it is challenging to fully understand the magnetization reversal occurring in Hall-bar devices based solely on electrical measurements. SOT-driven magnetization reversal is often explained as a result of the spin torque acting on a uniform magnetization. According to the mechanism, the threshold current required for magnetization reversal in a Hall-bar device can be interpreted as proportional to the overall average PMA of a device.

However, since the magnetic layer in typical Hall-bar devices extends beyond the Hall cross to all parts of the device, magnetization switching is often initiated in localized regions where the magnetic anisotropy is weakest, and domain wall motion subsequently leads to reversal of the entire magnetization. This makes it difficult to directly correlate the switching threshold current with the average anisotropy of the device. Additionally, in some cases, the AHE signal associated with SOT-induced magnetization switching appears weaker compared to that of the magnetic field-induced full magnetization reversal, suggesting that electrical measurements alone may not fully capture the underlying mechanisms within the Hall-bar device. To gain a deeper understanding, complementary analyses are necessary alongside electrical measurements [1,7,10-12].

Recent studies have employed magneto-optical Kerr effect (MOKE) microscopy imaging as an auxiliary method for investigating magnetization states during SOT switching, enabling a more precise analysis of the magnetization dynamics [1,14-18]. In particular, ferrimagnetic materials have been shown to exhibit unique switching patterns in the anomalous Hall voltage that differ from those of ferromagnets [13,16,18]. Therefore, when studying SOT-induced magnetization switching in such ferrimagnetic materials, imaging techniques such as MOKE microscopy can be even more effective.

In this work, we investigated SOT-induced magnetization switching in the ferrimagnetic GdFeCo/Pt system with bulk PMA, by simultaneously utilizing anomalous Hall voltage measurements and MOKE microscopy imaging. Our results show that in GdFeCo/Pt, magnetization reversal primarily occurs through domain wall motion. The AHE signal corresponding to SOT-induced magnetization reversal was observed to be slightly weaker compared to that of the magnetic field-induced reversal. It is found that the weaker signal is ascribed to the incomplete reversal in the Hall-bar where the electric current density significantly decreases.

II. Experimental Method

To conduct SOT switching experiments, we deposited a ferrimagnetic multilayer structure with bulk PMA, consisting of SiN (5 nm)/$Gd_{23}Fe_{67.4}Co_{9.6}$ (10 nm)/Pt (5 nm) deposited on a Si substrate with 100-nm SiO_2 layer, using DC magnetron sputtering. In this composition, the net magnetization at room temperature was found to align with that of the transition metal element (FeCo

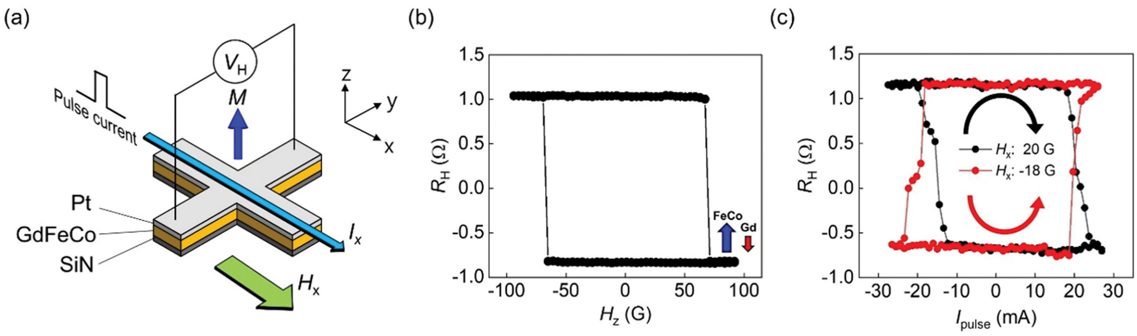

Fig. 1. (Color online) (a) Schematic illustration of the SOT switching experiment. (b) The anomalous Hall resistance as a function of the perpendicular magnetic field. (c) SOT switching curves both for opposite in plane magnetic fields.

atoms). The deposited films were then patterned into 50 μm-long and 15 μm-wide tracks with a single Hall bar via photolithography. Fig. 1(a) provides a schematic diagram of the sample structure and the experimental setup.

For AHE measurements, a weak DC probe current of 0.5 mA was used to minimize Joule heating effects. In the SOT switching experiments, the switching current I_{pulse} was applied in the form of pulses with a width of 50 μs. After each current pulse injection, we measured the anomalous Hall resistance using the DC probe current and simultaneously captured domain patterns with MOKE microscopy. All measurements were performed at room temperature.

III. Results and Discussion

Before performing SOT switching experiments, we first confirmed the presence of PMA in the GdFeCo/Pt sample by applying an out-of-plane magnetic field H_z and measuring the anomalous Hall resistance R_H as shown in Fig. 1(b). The results clearly indicate that the sample exhibits strong PMA. Here, the lower (or higher) R_H corresponds to the FeCo magnetization oriented in the $+z$ (or $-z$) direction.

Fig. 1(c) shows the SOT-induced magnetization switching in which R_H changes as a function of I_{pulse} with an in-plane magnetic field H_x applied along the current direction. We observed that I_{pulse} with an amplitude of approximately 20 mA could induce perpendicular magnetization reversal, and the switching polarity is reversed depending on the direction of the weak H_x. This confirms that the magnetization switching is driven by the damping-like SOT.

It is also noted that there is a slight offset in R_H between Figs. 1(b) and 1(c). This offset arises from the use of different measurement setups during the field-induced (Fig. 1(b)) and current-induced (Fig. 1(c)) magnetization reversal experiments. However, this offset does not affect the analysis of the magnetization state, as only the R_H difference between the $+z$ and $-z$ magnetization states is used for interpreting the magnetization switching.

Fig. 1(b) displays an almost clear rectangular hysteresis loop, indicating well-defined PMA in the field-induced magnetization reversal. In contrast, the SOT-induced magnetization reversal loops in Fig. 1(c) exhibits multiple distinct steps in R_H within the switching region. This suggests that the magnetization switching process occurs through intermediate states, due to randomly nucleated domains and then their propagation, rather than an abrupt reversal of the single macro magnetization. Additionally, when observing the lower R_H values as a function of I_{pulse}, it becomes apparent that the R_H levels differ slightly between the negative and positive I_{pulse} regions. This difference indicates that the reversed area in the Hall-bar device differs depending on the current polarity.

To investigate the unique characteristics of the SOT-driven magnetization switching, we employed MOKE microscopy in conjunction with electrical measurements

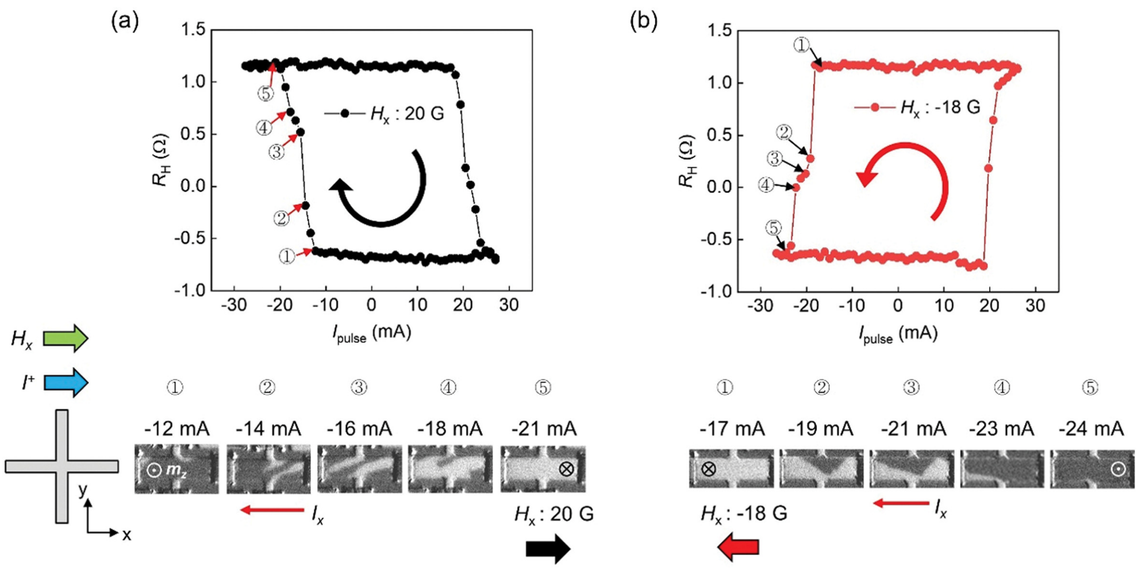

Fig. 2. (Color online) (a) The anomalous Hall resistance as a function of the pulse current with (a) H_x = +20 G, and (b) H_x = −18 G. The numbers indicate the intermediate state during the SOT switching with corresponding MOKE images in the bottom panels.

to image the magnetic domains during switching. Figs. 2(a) and (b) separately display the SOT-induced magnetization switching curves from Fig. 1(c), with Kerr images corresponding to specific R_H levels shown in the lower panels. In these images, bright contrast represents FeCo magnetization oriented in the $-z$ direction, while dark contrast corresponds to magnetization in the $+z$ direction.

As seen in the images, the magnetization switching, which occurs through multiple R_H levels, does not involve a uniform reversal across the entire device. Instead, the magnetization reversal in a device as wide as 15 μm begins in localized regions where the magnetic anisotropy is possibly weaker, and then spreads through domain wall motion, eventually reversing the magnetization in the Hall cross area.

In Fig. 2(a), examining states ①-③ reveals that the magnetization reversal starts near the upper Hall bar region in state ① and gradually expands in the $-x$ direction as $-I_{pulse}$ increases, indicating that the domain wall moves in the direction of the current. Similarly, in Fig. 2(b), a dark domain created in state ② also moves along the current direction.

The observation that the domain walls move even under a very weak in-plane magnetic field H_x (~20 G) suggests that the GdFeCo/Pt system likely supports inherent Néel-type domain walls, stabilized by the Dzyaloshinskii-Moriya interaction (DMI) [19,20]. In a recent report [21,22], due to its inherent bulk properties, the bulk DMI is present in this amorphous ferrimagnetic system.

Lastly, examining state ① in Fig. 2(a) and state ⑤ in Fig. 2(b) reveals the presence of domains with bright contrast in the Hall-bar. Notably, in state ⑤ of Fig. 2(b), although the R_H level indicates that the SOT-induced magnetization reversal is nearly completed, there are still unflipped domains within the Hall bar. This phenomenon accounts for the previously mentioned differences in R_H levels between $-I_{pulse}$ and $+I_{pulse}$ regions. Since the current predominantly flows along the x-direction of the device, the current density inside the Hall-bar could be nearly zero. Consequently, the magnetization within the Hall bar cannot be switched by the spin-orbit torque, which explains why unflipped domains remain even after the overall switching appears to be completed. This indicates that local variations in current density significantly impact the effectiveness of spin-orbit torque in inducing magnetization reversal within different regions of the device.

4. Conclusion

In summary, we measured SOT switching in the ferrimagnetic multilayer GdFeCo/Pt, which possesses PMA, and simultaneously captured the magnetization states using MOKE microscopy. We confirmed that magnetization reversal occurs through domain wall motion. We also find that the relative Hall resistance levels slightly differ in electrical measurements compared to those in magnetic field-induced anomalous Hall measurements. This is attributed to the fact that the magnetization within the Hall bar does not completely switch by SOT because of the non-uniform current density, while it can be completely reversed by the magnetic field which is uniform through the entire device.

Acknowledgement

This work was supported by the government (Ministry of Science and ICT) through funding from the National Research Foundation of Korea (No. 2020R1C1C1006194 and NRF-2022R1A2C2004493), the Korea Institute of Science and Technology (KIST) institutional program (grant 2E32951), and by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIT) (No. GTL24041-000).

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