Spin-Orbit Torque Driven Magnetization Switching and Precession by Manipulating Thickness of CoFeB/W Heterostructures

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The switching of magnetization via spin-orbit torque has attracted much attention because of its fast switching and low power consumption. Numerous studies have focused on increasing the conversion efficiency from charge to spin current and out-of-plane magnetization cases. Recently, there have been reports on the fast and deterministic switching of in-plane magnetization devices. It is reported that an in-plane spin-orbit torque (SOT) device can archive the oscillation, precession, and direct switching by a combination of torques—controlling the thickness of the ferromagnet and normal metal. With proper layer thicknesses, the device can show the three dynamics listed above at each current density in a macro spin simulation. Based on an understanding of the role of torque-driving magnetization dynamics, a dynamic map of an in-plane SOT device depending on torque efficiency and current density is shown.

1. Introduction

As the driving force for magnetization manipulation, spin-orbit torque (SOT) led to the development of various devices. One of the most useful advantages of SOT is its scalability.[11] Thus, numerous researchers have been interested in a number of small nano-devices operated by a low current density. In particular, it has been proposed to facilitate the electrical manipulation of magnetization switching for magnetic random access memory and magnetic logic devices by using these torques.[2–6] Moreover, an oscillation and precessional motion by SOT can be a candidate for various types of oscillators.[7–9]

The spin Hall effect (SHE) and the Rashba–Edelstein interaction are expected to be the main mechanisms of the current-induced SOT, where the two main constituents are the damping-like torque and field-like torque.[10–13] In the SHE, a spin current is generated in a direction perpendicular to the applied longitudinal charge current flowing in a normal metal (NM) and accumulates spins between FM and NM layers, which exerts a damping-like torque to the magnetization in FM.[14,15] In the Rashba–Edelstein effect, which is caused by the broken space inversion symmetry at the interface, spin accumulation is generated in a direction transverse to the charge current direction in the film plane, which exerts a torque on the magnetization in a ferromagnet (FM).[16–20] In addition to the spin Hall and Rashba–Edelstein effects, the Oersted field generated by the current in a metallic film is an additional source of driving torque.[21,22]

In a perpendicular magnetic anisotropy (PMA) structure, these torques generated from a nano-second electric pulse switch the magnetization by a domain wall motion.[23–25] It is known that the in-plane magnetic tunnel junction (MTJ) device by a spin transfer torque does not need an external field but takes a relatively long time for the switch due to an incubation time.[26,27] But, recently, researchers demonstrated an in-plane MTJ device by SOT showing a fast deterministic switching at a low current density.[28–31] This in-plane device offers various possibilities in application so that more intensive study is needed.

In this work, we investigated the new aspect of in-plane SOT device depending on the amplitudes of damping-like torque, field-like torque, the Oersted field torque and demagnetization torque by a macro spin simulation. We found that the switching, oscillation, and precession could occur in the same heterostructure like W/CoFeB by using the change of the torque ratio with different NM and FM thicknesses. In addition, we constructed the dynamic map as a function of the efficiency of each torque. The expansion and the shrinkage of the switching region are reflected in the map depending on the current density.

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2. Spin Torque Efficiencies and Torque Ratio in W/CoFeB Hetero Structure

We performed spin-torque ferromagnetic resonance (ST-FMR) measurements on W (5 nm)/CoFeB (t_{FM} nm)/MgO (2 nm)/Ta (1 nm) samples with variable CoFeB thickness (See Supporting Information S1 and S2 for material charaterizations). In the ST-FMR experiment, the microwave (MW) current induces a SOT and an Oersted field torque, which manipulates the magnetization in FM. Then, the resistance of the device largely oscillates simultaneously by the anisotropic magnetoresistance and spin Hall magnetoresistance because the magnetization resonates when FMR condition is satisfied. We measured the direct current (DC) voltage generated from the mixing of the MW current and oscillating resistance by the lock-in technique. The angle between the magnetic field and the long axis of the sample was \( \approx 45^\circ \) when the MW power was fixed at 10 dBm (Figure 1a).

In Figure 1b, we calculated FMR efficiency (\( \xi_{FMR} \)) which is expressed as

\[
\xi_{FMR} = \frac{S}{A} \left( \frac{e}{\hbar} \right) \mu_0 M_{eff} d_{NM} \sqrt{1 + \left( \mu_0 M_{eff} / H_k \right)}
\]

where \( A \) and \( S \) are the antisymmetric and symmetric Lorentzian components, \( M_{eff} \) and \( H_k \) are the effective magnetization and resonance field obtained from ST-FMR results, \( e, \hbar, \mu_0, M_s, t_{FM}, \) and \( d_{NM} \) are the electronic charge, reduced Plank's constant, vacuum permeability, and effective thicknesses of FM and NM, respectively.[33] The inset of Figure 1b shows the plot of \( 1/\xi_{FMR} \) versus \( 1/t_{FM} \). The damping-like torque efficiency \( \xi_{DL} = 2e/\hbar \mu_0 M_{eff} H_{DL} / J_c \) and the field-like torque efficiency \( \xi_{FL} = 2e/\hbar \mu_0 M_{eff} H_{FL} / J_c \) of W can be obtained from the slope and intercept of the linear fit, where \( H_{DL} \) and \( H_{FL} \) are damping-like torque and field-like torque fields. The values were \(-0.249 \pm 0.010\) and \(-0.060 \pm 0.002\), respectively. (About the inverse spin Hall effect in our system, see Supporting Information S3)

The inverse of FMR efficiency is proportional to the torque ratio between the perpendicular and horizontal torques (\( \tau_\perp \) and \( \tau_\parallel \)) generated by the charge current. At given thickness values of FM and NM, the torque ratio is expressed as

\[
\frac{\tau_\perp}{\tau_\parallel} = \frac{1}{\xi_{FMR}}
\]

Figure 1. Experimental results of ST-FMR. a) Schematic of the electrical circuit for ST-FMR measurement system. The stacked structure is the sample geometry of W (5 nm)/CoFeB (t_{FM} nm)/MgO (2 nm)/Ta (1 nm). b) FMR efficiency \( \xi_{FMR} \) as a function of FM thickness \( t_{FM} \). The blue line is a guide to eye. The inset shows inverse of each axis and a linear fitting result (red line). c) Ratio between a perpendicular and horizontal torques (\( \tau_\perp \) and \( \tau_\parallel \)) for various tungsten thicknesses (4–7 nm). Each solid curve is a linear fitting result. d) Schematic diagrams of analyzing the magnetization M, external magnetic field H, current density Jc, damping-like torque \( \tau_{DL} \), Oersted field torque \( \tau_{OE} \), field-like torque \( \tau_{FL} \), and Oersted field \( \tau_{OE} \). Arrows indicate the components of direction and relative strength. e) Contour map of torque ratio. A red dashed line is the zero perpendicular torque line (\( \tau_\perp = 0 \)).
We calculated the torque ratio for each FM and NM in Figure 1c. The torque ratio showed a linear curve at each NM thickness, as expected from Equation (2). The slopes were negative and the y-intercepts were positive because the damping-like torque and field-like torque were negative in our system. All the linear fitting curves intercept the x-axis, which means that Oersted field torque ($\tau_{Oe}$) and the field-like torque ($\tau_{FL}$) cancel each other and the resultant perpendicular torque is zero at each x-intercept. Below the zero perpendicular torque point, the field-like torque is larger than the Oersted field torque. Considering the relation between the torques, in Figure 1d, we draw the vectors of the field-like torque, Oersted field torque, and damping-like torque ($\tau_{DL}$), as well as the current density ($J_C$), and the Oersted field ($h_{Oe}$) for each CoFeB thickness for a W layer of 5 nm. The MW current density in the W layer decreased when the CoFeB thickness increased because we assumed that a constant MW power was applied on all devices. The contour map of the torque ratio based on ST-FMR result and Equation (2) is plotted in Figure 1e. The zero perpendicular torque line (ZPTL; $\tau_\perp = 0$) is positioned near the diagonal line of the square contour plot. As the position moves away from the ZPTL, the portion of perpendicular torque increases.

3. Macro Spin Simulation of In-Plane SOT Device

Using the torque efficiencies of the ST-FMR result, we simulated the macro-spin dynamics of a MTJ device with a 10 ns-current pulse of $3.5 \times 10^{12}$ Am$^{-2}$ (Figure 2a).1,28 The device is called as the type x in-plane SOT device, which is elongated along the flow direction of electric current (x-axis) and has the shape anisotropy along the same direction. Below the thickness of the ZPTL, deterministic magnetization switching occurs in contradiction to the oscillation and the precession region above the ZPTL in Figure 2b. The direct switching time ($t_{sw}$) is defined as the moment when $m_z$ is changed into negative value. Therefore, the direct switching time is a minimum pulse width for the switch. The frequency ($f$) is determined by the largest point of fast Fourier transform of $m_x$ with the cut-off frequency 50 MHz.

A decisive role in determining the magnetization dynamics can be made by the demagnetization field torque ($\tau_{demag}$) originating from the z-motion of the magnetization (Figure 2c). When this demagnetization field torque is parallel with the damping-like torque, fast switching occurs. The magnetization will align along $+y$ direction after damped oscillation. After 10 ns current pulse, the magnetization will relax along $-x$ direction as the anisotropy field is tilted toward $-y$ direction about one degree. If the direction of demagnetization field torque is opposite to and larger than the in-plane damping-like torque, then the magnetization starts to oscillate or precess. In the oscillation, the magnetization first rotates clockwise, but soon stops at some points in the $-x$ region and returns to $+x$ region. However, the magnetization circularly precesses in $xy$ plane in the precession region. The precession frequency is proportional to the difference between the integrations of the demagnetization field and damping-like torque field along $z$-axis during one period. (see Supporting Information S4).

At the initial stage of magnetization dynamics by the current pulse, the demagnetization field torque in the $xy$ plane originates from the sum of field-like and Oersted field torques because this overall torque acts to move the magnetization toward the $z$-direction as shown in Figure 2c. As the thickness values of FM and NM increase, the field-like torque decreases because the spin currents per unit area experience more magnetization to switch. However, since the Oersted field torque depends only on the thickness of the NM, its magnitude remains the same regardless of the FM thickness. By varying the thicknesses, we can manipulate the direction, and amplitude of the demagnetization field torque and the overall behavior of magnetization. Contour maps of the torque ratio (Figure 1e) and simulation result (Figure 2b) show a similar

**Figure 2.** Simulation results of type x in-plane device. a) Schematic diagram of the MTJ device of W ($d_{\text{NM}}$ nm)/CoFeB (10 nm)/MgO/CoFeB/Ru for macrospin model. A light blue arrow indicates the unit vector of the magnetization $\vec{m}$. b) Contour map of simulation result with current density $3.5 \times 10^{12}$ A m$^{-2}$ with various FM and NM thicknesses. 3D position diagrams of magnetization (blue circle) indicates dynamic motion of switching ($\tau_\perp < 0$) and precession ($\tau_\perp > 0$). c) 3D vector diagram of torques, demagnetization field $h_{demag}$, and motion of magnetization (green arrow) along $z$-axis at the initial stage of each dynamics. $\tau_{demag}$ indicates the demagnetization field torque.
aspect around the ZPTL because the torque ratio contains the relative direction and amplitude of the demagnetization field torque in comparison with the damping-like torque in xy plane at the initial movement of magnetization.

A main difference between PMA and in-plane magnetic anisotropy devices is the role of demagnetization field torque. In the PMA system, any torque does not act like the demagnetization field torque of in-plane system. The direction of demagnetization field is always antiparallel with a perpendicular anisotropy field, which results in a decrease of total effective anisotropy field along z-axis. Moreover, all torques are symmetric with respect to xy plane and converge to 0 as the magnetization approaches the xy plane in PMA system. However, the demagnetization field torque is willing to circularly rotate the magnetization unless the magnetization is tilted along z-axis in the in-plane system.

We also simulated the device with various currents (Figure 3). With the decrease in current density, the white region expands in Figure 3a. This is natural because the amplitudes of the driving torques depend on the current density. For the same reason, as the current density gradually increases, the precession frequency also increases in the region far from ZPTL. However, near ZPTL above a certain current density, the device abruptly starts to switch. For example, with the point located at a red star, in contrast with the oscillation and precession dynamics of the magnetization for low and moderate current densities (Figure 3a–c), the magnetization shows switching dynamics at $6 \times 10^{12}$ Am$^{-2}$ in Figure 3d. This is due to an out-of-plane damping-like torque suppressing the effect of the Oersted field torque. When the magnetization very rapidly moves toward the y-axis at the initial stage of precession with a high current density, the additional out-of-plane damping-like torque \((\gamma \sigma_\gamma \times (\mathbf{m} \times \sigma_\gamma))\) is generated along z-axis and competes with the Oersted field torque. Under the effect of the additional torque, the magnetization moving toward the z-axis cannot go far and returns to the xy plane. Therefore, the demagnetization field torque is not large enough to cause precession. Eventually, the overall dynamics of magnetization is governed by the in-plane damping-like torque in xy plane, which results in the magnetization switching with the high current density.

Figure 3e shows the time evolution of $m_z$ component during 10 ns current pulse at each current densities. In the low current region, oscillating $m_z$ between + and − regions indicates a sign oscillation of demagnetization field. However, at the moderate current densities, $m_z$ is always positive due to a sufficient acceleration by the in-plane damping-like torque in −x region, which results in the circular motion of magnetization in xy plane. Based on these results, a single device for oscillation, precession, and switching can be made depending on the current density without an external field.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Simulation results with various current densities. a–d) Contour maps of torque ratio with various current densities. Red dashed lines are the zero perpendicular torque line. e) Time evolution of z-axis magnetization at each current density with the 5.75 and 6 nm FM thicknesses (red star). The dynamics of magnetization is categorized by three regions—switching, precession, and oscillation. Gray dashed lines mean $m_z = 0$ at each current densities.
4. Dynamics Map of In-Plane SOT Device

Based on the analysis discussed above and the simulated results, the dynamic map with damping-like torque and field-like torque is plotted in Figure 4a. The purple dotted line crossing the y-axis in the negative field-like torque efficiency region is the ZPTL \( (ξ_{z\text{FL}} = -\frac{e}{\mu}\mu_s M_t d_m) \). The sign of the perpendicular torque changes around this line at the low-current density. For the positive perpendicular torque and damping-like torque, only clockwise switching of the magnetization occurs. As the perpendicular torque increases, the movement of the magnetization by the demagnetization field torque becomes faster. The large damping-like torque also helps the fast-switching because the magnetization dynamics could be stabilized quickly due to an additional damping effect.

With a negative damping-like torque, the magnetization easily precesses in addition to the antidamp effect. If the antidamping effect is smaller than the damping effect of FM, the magnetization is finally switched on with the long current pulse. However, if the antidamping effect is larger than the damping effect, the device shows the precession of magnetization. A precession frequency is determined by the combination of the field-like torque, Oersted field torque, damping-like torque and Gilbert damping torque along the z-axis because the averaged magnetization along the z-axis is directly related to the precession frequency. (see Supporting Information S5) Between the precession and switching regions, there is the oscillation region, where the magnetization just oscillates in xy plane and does not precess along z-axis due to shortage of acceleration by the damping-like torque. The switching and oscillation regions are divided by the equation

\[
ξ_{\text{DL}} = \pm e' \frac{M}{H_{\text{SOT}}} \alpha 
\]  

where \( \alpha \) and \( e' \) are the Gilbert damping constant and numerical factor, respectively. \( H_{\text{SOT}} \) is the magnetic field generated from SOT when each efficiency equals unity \( (= \frac{1}{2} \mu M_t J_{\text{FM}}) \).

In the case of negative perpendicular torque, the magnetization rotates counterclockwise. Therefore, the roles of all torques are reversed, which results in a symmetrical structure to point \((0, -ξ_{z\text{FL}})\) in the dynamic map.

As the current density increases, the switching region expands because of the additional demagnetization field torque generated from the damping-like torque along the z-axis. The line dividing the dynamic map into CW and CCW regions in the negative field-like torque efficiency region is expressed as

\[
ξ_{\text{FL}} = ± e'' \frac{M}{H_{\text{SOT}}} (ξ_{\text{DL}}) - ξ_{z\text{FL}} ± e' H_{\text{ani}} \frac{H_{\text{SOT}}}{H_{\text{SOT}}} 
\]

where \( H_{\text{ani}} = (= \frac{K_u}{\mu M_s}) \), \( e', \) and \( e'' \) are the anisotropy field and the numerical factors, respectively, where \( K_u \) is an anisotropy energy. Therefore, by controlling the thickness of the FM and/or NM layers, we can make a device that shows only switching, precession, or both with a given range of current density (for the numerical factors and the role of the anisotropy field, see Supporting Information S6 and S7).

5. Conclusion

In conclusion, we have demonstrated the three dynamics (switching, oscillation, and precession) of type-x in-plane SOT devices by employing perpendicular and horizontal torques obtained from the ST-FMR results of the W/CoFeB heterostructures. In the region where the amplitude and direction of the Oersted field and field-like torques were similar and opposite, we found that the magnetization switches, oscillates,
or precesses depending on the current density without an external field. Based on our understanding of the magnetization dynamics in this paper, we made a dynamic map of the device as a function of the damping-like torque efficiency and field-like torque efficiency. In future works, the dynamic map will be an important navigator in developing the in-plane SOT device.

6. Experimental Section

Sample Growth and Preparation: All samples were deposited on Si (100) wafers with 300-nm-thick thermally oxidized SiO2 layers. A six-target DC magnetron sputtering system was used for depositing the W, CoFeB, and Ta layers at a base pressure below 5 × 10^{-9} Torr. The power density was fixed at 1.9 W cm^{-2} and the Ar (6N purity) gas pressure was kept constant at approximately 2 mTorr. The composition of the CoFeB target was Co40Fe40B20 (at%) and the purity of the W and Ta targets was 99.99%. The insulating MgO layer was deposited by radiofrequency sputtering at a base pressure below 8 × 10^{-9} Torr. The samples were prepared as follows: Si/SiO2/W(5 nm)/CoFeB (t_{FM} nm)/MgO (2 nm)/Ta (1 nm). The Ta–capping layer served as a protective layer and the thickness t of the CoFeB layer ranged between 2.5 and 9 nm. The magnetic properties were measured using a vibrating sample magnetometer at room temperature. To characterize the microstructure of the films, an X-ray diffractometer with Cu Kα radiation was used. A photolithographic patterning procedure including ion beam etching was used to fabricate the bar shape microstrip devices with the dimensions 20 × 70 μm². The metal contacts consisted of 65-nm-thick Au and 5 nm Ti; the latter served as an adhesive layer.

Characterization: ST-FMR was used to observe the SHE; 10 dBm MW power was applied along the length of the sample using an analog MW signal generator, and the output DC voltage was measured using the lock-in technique.

Macro-Spin model: the SOT-induced dynamics was calculated using the macro-spin model described by the Landau–Lifshitz–Gilbert equation with additional torques, namely the damping-like torque and field-like torque:

\[ \frac{d\vec{m}}{dt} = -\gamma \mu_0 \vec{H}_{\text{eff}} + \alpha \vec{m} \times \frac{d\vec{m}}{dt} + \gamma \alpha_0 \vec{m} \times (\vec{m} \times \vec{d}) + \gamma \alpha_1 \vec{m} \times \vec{d} \]

where \( \gamma \) is the gyromagnetic ratio, \( \vec{m} \) is the unit vector of the magnetization, \( \mu_0 \vec{H}_{\text{eff}} \) is the effective magnetic field including the external, anisotropy, magnetostatic, exchange, and demagnetization fields, and \( \alpha \) is the damping constant (=0.02). \( t_{DL} = (h/2\gamma J_s M_{\text{FM}} t_{FM}) S_{DL} \) and \( t_{PL} = (h/2\gamma J_s M_{\text{FM}} t_{FM}) S_{PL} \) show the magnitudes of the damping-like torque and field-like torque, respectively, in the magnetic field unit, where \( J_s \) is the charge current density, \( M_{\text{FM}} \) is the saturation magnetization (=1.0 MA m^{-1}), \( t_{FM} \) is the thickness of the FM layer from 5.0 to 7.0 nm, \( S_{DL} \) (\( -0.267 \)) and \( S_{PL} \) (\( -0.0528 \) to \(-0.0670 \)) are the damping-like torque efficiency and field-like torque efficiency, respectively, and \( \vec{d} \) is the unit vector perpendicular to both the current and inversion asymmetry directions (i.e., thickness direction; see the coordinate system in Figure 2a). In the configuration, the shape anisotropy energy density \( K_{\text{ani}} = 1 \text{ kJ m}^{-2} \), which is tilted +1° (CCW switching) or -1° (CW switching) from the current direction (x-axis), was adopted to accomplish the deterministic magnetization switching. The direct switching time and the precession (and the oscillation) frequency are defined at the moment of \( m_{s} < 0 \) and by the fast Fourier transform of the temporal trajectory of \( m_{x} \), respectively. All calculations assumed that the Oersted field generated from the current in NM is only valid because the Oersted field from FM is self-cancelled and cannot influence the dynamics of device. Although a current shunting effect is important to evaluate the realistic efficiency of device with different thicknesses of FM and NM, this effect was not discussed in this article to analyze three dynamics of device based on the underlying torque ratios depending on thicknesses of FM and NM, briefly.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

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