Spin–orbit torque driven magnetization switching in W/CoFeB/MgO-based type-Y three terminal magnetic tunnel junctions

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We have studied current induced magnetization switching in W/CoFeB/MgO based three terminal magnetic tunnel junctions. The switching driven by spin–orbit torque (SOT) is evaluated in the so-called type-Y structure, in which the magnetic easy-axis of the CoFeB layer lies in the film plane and is orthogonal to the current flow. The effective spin Hall angle estimated from the bias field dependence of critical current ($I_c$) is $\sim 0.07$. The field and current dependence of the switching probability are studied. The field and DC current induced switching can be described using a model based on thermally assisted magnetization switching. In contrast, the 50 ns long pulse current dependence of the switching probability shows significant deviation from the model, even if contribution from the field-like torque is included. The deviation is particularly evident when the threshold switching current is larger. These results show that conventional thermally assisted magnetization switching model cannot be used to describe SOT induced switching using short current pulses.

The spin–orbit torque (SOT) magnetoresistive random access memory (MRAM) is one of the emerging technologies for next generation memory devices1,2. In SOT-MRAM, current is passed along a channel made of a non-magnetic heavy metal (HM) layer on which a magnetic tunnel junction (MTJ) is placed. The current passed along the HM layer generates spin current via the spin Hall effect that diffuses into the ferromagnetic free layer of the MTJ. Such spin current exerts SOT3–5 on the free layer magnetization. With appropriate condition, the SOT can induce magnetization switching depending on the direction to which the current flows within the channel. As the current needed to write information (i.e. switch the magnetization) does not flow across the tunnel barrier, the three terminal SOT-MRAM is considered to possess larger endurance compared to the conventional two terminal STT-MRAM6.

The three terminal SOT-MRAM can be categorized into three types7 depending on the geometry of the MTJs and the SOT channel: type-X, Y, Z refers to, respectively, magnetic easy-axis of the free layer of the MTJ pointing along the current flow direction (type-X), orthogonal to the current flow direction but lies in the film plane (type-Y), and perpendicular to the film plane (type-Z). It is now well understood that the switching dynamics of the three types are different. While types-X and Z allow sub-nanosecond switching of the magnetization7–9, type-Y requires nanoseconds long incubation time to cause the switching4,10,11. On the other hand, magnetization can be controlled in type-Y12 without any magnetic field, whereas a dc bias magnetic field is needed during the current application process for types-X and Z. The switching scheme of type-Y is close to that of conventional STT-MRAM. As field-free switching schemes for types-X and Z devices are currently being developed, the most straightforward approach to replace STT-MRAM with SOT-MRAM is to use the type-Y device.

Here we study SOT induced magnetization switching probability of type-Y three terminal MTJ. We use tungsten (W) as the channel material and CoFeB/MgO/CoFeB as the base element of the MTJ. The switching probability with DC current and pulse current are investigated and compared to model calculations based on

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thermally assisted magnetization switching. We include the field-like torque in the model in an attempt to account for the experimental results.

### Results and discussion

#### Device structure and magnetization switching by field and current.

**Figure 1a** shows schematic illustration of the three terminal MTJ consisting of a W channel and the elliptical MTJ pillar. The MTJ consists of MgO barrier sandwiched by a CoFeB free layer and a CoFeB-based synthetic-antiferromagnet (SAF) pinned layer. The thickness of the free layer is 2 nm. The coordinate axis is sketched in Fig. 1a. The short and long axes of the elliptical MTJ pillar are 120 nm and 370 nm, respectively. The long axis of the pillar, which corresponds to the magnetic easy-axis of the free layer due to shape anisotropy, is parallel to the y-axis. The pinned layer magnetization points along +y. A variable amplitude pulse current (I_p) with duration (t_p) fixed to 50 ns or DC current (I_DC) (duration is ~1 s) is applied to the W channel to induce magnetization switching along the x-axis. The pulse and DC current sources are different. Note that the rise and fall time of the DC current is significantly larger than those of the pulse current but are sufficiently smaller than the duration of the current (~1 s). Current passed along the W channel is parallel to the y-axis; positive current is defined as current flowing along +y. The geometry of the device used here is referred to as type-Y. To probe the magnetic state of the MTJ free layer, a DC bias voltage of 10 mV is applied to the MTJ. An external field H_y (solid triangles) and −0.63 μA/Oe (solid circles), which are smaller than those for the pulse current. In the case of DC current, we obtain −0.44 μA/Oe (open triangles) and −0.33 μA/Oe (open circles), which are smaller than those for the pulse current.

We have studied more than 15 devices with nominally the same device structure. Representative results from one device are shown: similar data are obtained for the other devices. All measurements are performed at room temperature.

**Figure 1b** shows the minor loop of the MTJ resistance (R_MTJ) vs. H_y. The high (~64 kΩ) and low (~36 kΩ) resistance states correspond to antiparallel (AP) and parallel (P) alignment of the free and pinned layers' magnetization. The tunnel magnetoresistance (TMR) ratio and the resistance-area product are ~78% and ~1600 Ωμm², respectively. As H_y is swept, switching from P to AP (AP to P) states are found at H_y = ~100 Oe (~210 Oe). The center of the minor loop is shifted to +H_y, which is due to the stray field from the pinned layer and/or the orange peel coupling of the free and pinned layers. The shift field, defined as H_s, is ~54 Oe.

**Figure 1c** shows the R_MTJ-I_p loop measured with a constant bias field H_y = 54 Oe. We pass a current pulse (50 ns long) through the W channel and measure the MTJ resistance while H_y is applied. The amplitude of the current pulse is varied from I_p = +550 μA to −550 μA and then reversed. The SOT switching from P to AP (AP to P) is observed at I_p = 390 μA (~−380 μA). The change in the MTJ resistance R_MTJ is consistent with the R difference of the P and AP magnetic states. We define I_p(AP) as the switching current when the initial state is the P (AP) state.

#### Evaluation of the effective spin Hall angle.

**Figure 2** displays I_p(AP) as a function of H_y. The solid circles and triangles show I_p and I_p(AP), respectively, using 50 ns long pulse current. We find |I_p(AP)| increases when H_y increases the barrier height of the switching. For example, the lower energy state is the AP (P) state when H_y < H_s (H_s > H_s). |I_p(AP)| is therefore larger than |I_p| when H_y < H_s. This is consistent with STT induced magnetization switching. The switching current |I_p(AP)|, when the pulse current is replaced with a DC current (duration 1 s) is shown by the open symbols in Fig. 2. We fit the data with a linear function to compare the slopes for pulse and DC current. The solid lines in Fig. 2 represent the least square fitting results. The estimated slopes are ~1.18 (solid triangles) and ~0.63 μA/Oe (solid circles) for the pulse current. In the case of DC current, we obtain ~0.44 (open triangles) and ~0.33 μA/Oe (open circles), which are smaller than those for the pulse current.

The inverse of the slope in Fig. 2 corresponds to the damping-like spin orbit effective field (h_DL) per unit current acting on the magnetization divided by the Gilbert damping constant α (see Methods). We find that the...
Figure 2. $H_y$ dependence of the switching current $I_c(P,AP)$. The circles and triangles represent the switching from parallel (P) to antiparallel (AP) states ($I_c^P$) and from AP to P states ($I_c^{AP}$), respectively. The solid and open symbols correspond to $I_c^{P(AP)}$ when pulse current (50 ns long) and DC current (1 s long) are used, respectively. Solid lines represent fitting a linear function to the data.

The circles and triangles represent the switching from AP to P states ($I_c^{AP}$) and from P to AP states ($I_c^P$), respectively. The solid and open symbols correspond to $I_c^{P(AP)}$ when pulse current (50 ns long) and DC current (1 s long) are used, respectively. Solid lines represent fitting a linear function to the data.

averaged $h_{DL}/\alpha$ is $\sim 12.3$ Oe ($\sim 29.0$ Oe) at a channel current density ($j$) of $10^6$ A/cm$^2$ for pulse (DC) current. (The current density is estimated by assuming a uniform current flow within the channel.) We infer that difference in $h_{DL}/\alpha$ estimated using the pulse and DC current measurements may be caused by difference in the switching regime (e.g. dynamical switching vs. thermally activated switching$^{17}$). $h_{DL}$ per current density is related to the effective spin Hall angle $\xi$ via $h_{DL} \sim h\xi/(2eM_s d)$, where $M_s$ and $d$ are the saturation magnetization and thickness of the free layer$^4$. Substituting $M_s \approx 1200$ emu/cm$^3$ and $\alpha \approx 0.04$ estimated in a similar system$^{12}$ and $d = 2$ nm, we find $\xi \approx -0.03(-0.07)$ for the pulse (DC) current induced switching. We consider $\xi$ estimated from DC current induced switching is more accurate due to the smaller $I_c^{P(AP)}$; see Methods for the details. Note that $\xi$ is smaller than that estimated in previous works$^{10,14,18}$ likely due to damages caused by device fabrication processes (e.g. Ar ion etching of the CoFeB free layer that needs to be stopped right above the W layer).

**Current and field dependence of the switching probability.** The switching probability of the free layer is obtained using the following process: (1) Reset the free layer magnetization direction to either P or AP state using $H_s = \pm 1000$ Oe. (2) Measure the MTJ resistance at $H_s = 0$. (3) Apply a bias field $H_y$. For field-induced switching, we vary the amplitude and length of the bias field. To study current-induced switching, a pulse or DC current with variable amplitude is applied subsequently. (4) Measure the MTJ resistance at $H_y = 0$. The difference of the MTJ resistance acquired in processes (2) and (4) provides information on the magnetic state of the free layer. Processes (1)-(4) are repeated 20–50 times to obtain the switching probability.

Figure 3a,b show the probability of field-driven magnetization switching plotted as a function of $H_y$. The duration of $H_y$ in process (3), denoted as $t$, is varied. The switching probability changes from 0 to 1 as the magnitude of $H_y$ is increased. The transition of the switching probability from 0 to 1 is relatively sharp and shows little dependence on $t$. The switching characteristics of DC and pulse current induced magnetization switching are shown in Figs. 4 and 5, respectively. The duration of the pulse current is fixed to 50 ns (DC current is applied for ~1 s) and the bias field $H_y$ is varied. Note that $H_y < H_s$ ($H_s > H_y$) favors the AP (P) state ($H_s \sim 54$ Oe). The transition of the switching probability, from 0 to 1, is sharp and nearly independent of $H_s$ for the DC current induced switching. For $H_y \sim H_s$, the transition shows a slight broadening when $P$ approaches 1, a feature that is enhanced for pulse current induced switching.

In contrast, the transition shows a strong dependence on $H_s$ for pulse current induced switching. First, for $H_s \sim H_y$, we find a tail in the transition from 0 to 1 near $P \sim 1$, which was also apparent in the DC current switching. Although one may infer that such reduction in the switching probability at near zero (net) magnetic field is associated with magnetization switching processes that involve motion of domain walls, we do not find evidence of intermediate resistance states that correspond to domain walls remaining in the element after application of the current pulse. In addition, we find the transition width for which $P$ varies from 0 to 1 depends on $H_y$. The transition width tends to increase when $H_y$ is varied in a way to increase the barrier height for switching. This is not in line with the conventional view of thermally activated magnetization switching.

To show this discrepancy, the switching probability is calculated using a model based on thermally activated magnetization switching, given by$^{19}$

$$I_c \sim h_{DL}/(\alpha \xi).$$

$$h_{DL} \sim h\xi/(2eM_s d).$$

$$M_s \approx 1200 \text{ emu/cm}^3, \quad \alpha \approx 0.04.$$
Figure 3. (a, b) Magnetization switching probability plotted as a function of magnetic field ($H_y$). The duration of the field is 5 s (a) and 30 s (b). Symbols represent experimental data, the red solid lines show the fitting results using Eq. (1). The parameters used are: $H_K$ : 300 Oe, $H_s$ : 54 Oe, $\Delta P$ = $\Delta A_P$ : 85 and $I$ = 0. The arrows represent $H_c$ obtained in Fig. 1(b).

Figure 4. (a–c) Magnetization switching probability plotted as a function of the DC current $I_{DC}$. The bias field $H_y$ is varied as indicated. Switching probability is obtained using 1 s long DC current. Symbols represent experimental data, the red solid lines show the fitting results using Eq. (1). The parameters used for the fitting are listed in Table 1.
where $\tau_0$, $t$, and $H_K$ represent the inverse of the attempt frequency, the duration of the driving force (current or bias field $H_y$), and the in-plane magnetic shape anisotropy field, respectively. $\tau_0$ is fixed to 1 ns here for simplicity.

$P = 1 - e^{-\nu t}$,

$$\nu = \frac{1}{\tau_0} \exp \left\{ -\Delta_{P} \left( \frac{1 - \frac{H_y - H_S + h_{FL} I}{H_K}}{1 - \frac{I}{I_{PC}^{(P)}}} \right)^2 \left( 1 - \frac{I}{I_{PC}^{(P)}} \right) \right\} \text{ for } \text{AP} \rightarrow \text{P},$$

$$\nu = \frac{1}{\tau_0} \exp \left\{ -\Delta_{P} \left( \frac{1 + \frac{H_y - H_S + h_{FL} I}{H_K}}{1 - \frac{I}{I_{PC}^{(P)}}} \right)^2 \left( 1 - \frac{I}{I_{PC}^{(P)}} \right) \right\} \text{ for } \text{P} \rightarrow \text{AP},$$

Figure 5. (a–c) Magnetization switching probability plotted as a function of the pulse current amplitude $I_p$. The bias field $H_y$ is varied as indicated. Switching probability is obtained using 50 ns long pulse current. Symbols represent experimental data, the red solid, blue dashed and green dotted lines show the switching probability calculated using Eq. (1) with different $h_{FL}$. The parameters used for the fitting are listed in Table 2.
The effective spin Hall angle is estimated to be −0.07. We find the model can account for the field-induced magnetization switching, as a function of easy axis bias magnetic field, are evaluated and compared to calculations based on thermally activated switching. In general, larger barrier height leads to smaller transition width for such switching process. Here, however, the field-like SOT scales with the current. Therefore, increase in current leads to further increase in the barrier height via the field-like SOT, which causes the transition broadening. Thus positive $h_{DL}$ tends to increase the transition width.

### Discussion

Finally, we discuss possible mechanisms that cause the anomalous $H_y$ dependence of the transition width of the pulse current induced magnetization switching probability. First, it is possible that incoherent magnetization switching that involves nucleation and subsequent motion of domain walls can cause such broadening of the switching probability. However, we do not find intermediate resistance states (after application of current pulses) that suggest presence of domain walls in the free layer. The broadening is thus not caused by simple domain wall switching probability. However, we do not find intermediate resistance states (after application of current pulses) that suggest presence of domain walls in the free layer. The broadening is thus not caused by simple domain wall switching. Instead, we analyzed the data using a modified Eq. (1) that takes into account Joule heating. Here we assumed the barrier pinning effects. Current induced Joule heating may also play role in the switching process. For this purpose, we modified the equation by the effective spin Hall angle $	heta$ via

$$h_{DL} = \frac{\Delta \alpha_{AP} (\mu A)}{I_{AP} (\mu A)}$$

This is evident from the plots shown in Fig. 5b. Increase in $|P^{AP}|$ indicates larger barrier height for thermally activated switching. In general, larger barrier height leads to smaller transition width for such switching process. Here, however, the field-like SOT scales with the current. Therefore, increase in current leads to further increase in the barrier height via the field-like SOT, which causes the transition broadening. Thus positive $h_{DL}$ tends to increase the transition width.

### Methods

The damping-like spin orbit effective field ($h_{DL}$) relates to the effective spin Hall angle $\theta$ via

### Table 1.

| $H_y$ (Oe) | $\Delta_p$ | $\Delta_{AP}$ | $I_{AP}^P (\mu A)$ | $I_{AP}^{\text{th}} (\mu A)$ | $h_{DL}$ (Oe/μA) |
|-----------|-----------|----------------|----------------|----------------|----------------|
| (a) −54   | 85        | 85             | −270           | 550            | 0              |
| (b) 54    | 85        | 85             | −320           | 365            | −0.4           |
|           |           |                | −340           | 380            | 0              |
|           |           |                | −400           | 500            | 0.4            |
| (c) 136   | 85        | 85             | −390           | 330            | 0              |

**Table 1.** Parameters used to fit the experimental data on DC current induced switching. The other fixed parameters are: $H_K = 300$ Oe, $H_s = 54$ Oe.

### Table 2.

| $H_y$ (Oe) | $\Delta_p$ | $\Delta_{AP}$ | $I_{AP}^P (\mu A)$ | $I_{AP}^{\text{th}} (\mu A)$ | $h_{DL}$ (Oe/μA) |
|-----------|-----------|----------------|----------------|----------------|----------------|
| (a) −54   | 85        | 85             | −270           | 550            | 0              |
| (b) 54    | 85        | 85             | −320           | 365            | −0.4           |
|           |           |                | −340           | 380            | 0              |
|           |           |                | −400           | 500            | 0.4            |
| (c) 136   | 85        | 85             | −390           | 330            | 0              |

**Table 2.** Parameters used to fit the experimental data on pulse current induced switching. The other fixed parameters are: $H_K = 300$ Oe, $H_s = 54$ Oe.
where $j$ is the current density flowing in the W channel along the x direction, $M_s$ and $d$ are the saturation magnetization and thickness of the free layer. The critical current density of in-plane magnetized free layer at zero temperature is given by\(^\text{28}\)

$$j_c = \frac{2\pi e M_s d}{\hbar} \left( H_r + H_K + \frac{H_{\text{demag}}}{2} \right),$$

where $\alpha$, $H_K$, and $H_{\text{demag}}$ are the Gilbert damping constant, in-plane magnetic anisotropy field, and perpendicular magnetic anisotropy field, respectively. The in-plane magnetic anisotropy field originates from the shape anisotropy\(^\text{12}\), and is primarily determined by the demagnetization coefficients $N_i$ ($i = x, y, z$) via $H_K = 4\pi M \left( N_z - N_x \right)$. The perpendicular magnetic anisotropy field is given by $H_{\text{demag}} = 4\pi M \left( N_z - N_x \right) - H_{K,\perp}$, where $H_{K,\perp}$ represents the interfacial perpendicular magnetic anisotropy field\(^\text{26–28}\). Equations (1) and (3) are commonly used to analyze the probability of spin-transfer torque switching\(^\text{29}\), where it is often assumed that the effective switching barrier height linearly depends on the current when the current pulse-width is sufficiently long\(^\text{30–32}\). When the pulse width of the current is narrow, a large current will be necessary to induce a fast switching. A large current suppresses the effective switching barrier significantly, and as a result, the high energy-barrier assumption\(^\text{13}\) used in the derivation of Eq. (1) becomes no longer applicable. Therefore, the DC current induced switching measurement provides more accurate value of the effective spin Hall angle compared to that estimated by using the pulse current. From Eqs. (2) and (3), $h_{DL}$ per current density can be estimated as $d j_c / d H_y = \alpha j / h_{DL}$.

### Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**Author contributions**

S. I. performed experiments based on discussion with Y. S., T. T., S. M., T. S., and M. H. The samples were fabricated by Y. S., A. T., E. K., Y. I., K. H., and T. S. All authors discussed the results, and S. I., T. T., and M. H. wrote the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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