Dependence of spin-orbit torque effective fields on magnetization uniformity in Ta/Co/Pt structure

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The spin-orbit torque (SOT) effective fields, namely field-like and damping-like terms, depend on the thicknesses of heavy metal (HM) and ferromagnetic metal (FM) layers, in a stack comprising of HM/FM/HM or oxide. In this work, we report on the dependence of the SOT effective fields on the magnetization uniformity in the wires comprising of Ta/Co/Pt layer structure. SOT dependence on magnetization uniformity dependence was investigated by concurrent variation of the magnetization uniformity in Co layer and characterization of the SOT effective fields in each wire which excludes the layer thickness dependence influences. Our experimental results reveal that the field-like term decreases while the damping-like term increases with increasing Co magnetization uniformity. The magnetization uniformity influence on the effective fields is attributed to the spin Hall effect, which contributes to the SOT.

The control of magnetization switching in magnetic structures by an electric current is crucial for the development of spintronics devices1. An established approach is via spin-transfer torque (STT) which involves the transfer of angular momentum from spin-polarized current to the magnetization2. Lately, current-induced spin-orbit torque (SOT) has emerged as an efficient alternative to STT3,4. The SOT is observed in magnetic multilayer structures composed of a ferromagnetic (FM) layer sandwiched by two heavy metal (HM) layers5–7. In this structure, the conduction electrons of FM and HMs exhibit strong spin-orbit coupling which leads to two well-known phenomena, i.e., the Rashba effect and the spin Hall effect (SHE)3,4. Due to the Rashba effect, spins accumulate in the FM layer, which exerts both a damping-like and field-like torque on the magnetization of FM layer8. Meanwhile, due to SHE, polarized spins are induced to accumulate at the FM/HM interface and diffuse into FM layer, which gives rise to an STT effect on the magnetization9. The torque from the Rashba effect and SHE is namely the SOT comprising of a field-like torque and damping-like torque. Generally, the two torques are represented by the two corresponding effective fields, field-like term $H_F$ and damping-like term $H_D$3–7,9,10.

The dependence of the two effective fields on the orientation of the magnetization has been studied, especially in materials with perpendicular magnetic anisotropy (PMA)11–17. Reported SOT measurements on Ta/CoFeB/MgO structures have shown that the damping-like term $H_D$ changed the direction when the magnetization is reversed12. Recently, the dependence of the field-like term $H_F$ which has been considered as a constant on the polar angle of magnetization was observed experimentally in films with PMA14,15. The SOT effective fields also depend on the thicknesses of the FM and HM layers in Ta/CoFeB/MgO structure14. The increase of both field-like and damping-like terms with respect to the thickness of Ta has been reported, which is due to a more significant amount of current in a thicker Ta layer. For the dependence on the thickness of the FM layer, the field-like term decreases with increasing CoFeB thickness, while the damping-like term remains constant. Such dependence was ascribed to the giant magnetoresistance effect18. In the investigations of the referred dependences, sweeping magnetic fields were used. However, the sweeping behavior, i.e., magnetizing process, gives rise to magnetization variation or magnetization non-uniformity in magnetic devices. Hence, to precisely characterize the dependencies, the relationship between the SOT effective fields and the magnetic uniformity is required. Specifically, this relationship in a magnetic system with in-plane magnetic anisotropy (IMA) shows promising application in spintronics19.

Here, we demonstrate the dependence of the SOT effective fields on the magnetization uniformity in wires consisting of Ta/Co/Pt layers with IMA. The impact of HM and FM layers thickness dependence of SOT is...
eliminated. Varying the uniformity and characterizing the SOT effective fields were achieved concurrently in each wire by applying a magnetic field along the long axis of the wire. Experimental results show that the field-like term decreases with respect to the magnetization uniformity, whereas the damping-like term increases. It is proposed that the magnetization uniformity increase leads to an increase of electron diffusion constant to decrease the field-like term and increase damping-like term.

**Experiments and Discussion**

Harmonic Hall resistance measurement technique, which has been reported earlier20,21, were employed to characterize the SOT effective fields. In this technique, a constant field, $H_{x,ext}$, is applied longitudinally to the wire long axis to ensure a constant magnetization uniformity, while a transverse field to the wire, $H_{y,ext}$ is swept in the plane to obtain the SOT effective fields accurately. The transverse field changes the magnetization azimuthal angle $\phi_0$. With $H_{x,ext}$ being constant, the cosine of the angle, $X$, which can be simultaneously calculated by $X = \cos \phi_0 = H_{x,ext} / \sqrt{H_{x,ext}^2 + H_{y,ext}^2}$. $X$ is used to apply in the expression of the second harmonic Hall resistance $R_{2ndHall}$ as follows:

$$R_{2nd Hall} = \frac{R_{AHF}H_{x}}{2H_{x}} + \frac{R_{PHE}}{H_{x,ext}}H_{y}(2X^4 - X^2),$$

(1)

where $H_{D}$ and $H_{F}$ are the damping-like term and field-like term, respectively, $R_{AHF}$ and $R_{PHE}$ are the amplitudes of anomalous Hall effect and planar Hall effect resistances, and $H_{x}$ is the effective field orientating the magnetization in the film plane. By fitting the experimental second harmonic Hall resistance with Eq. (1), the SOT effective fields can be extracted. In Eq. (1), the parameter $R_{PHE}/H_{x,ext}$ can be obtained from the first harmonic Hall resistance $R_{1stHall}$ which is expressed as $R_{1st Hall} = R_{PHE} \sin 2\phi_0$. Due to the expression of $\cos \phi_0$, the maximum and minimum values of $R_{1st Hall}$ occur at $H_{y,ext} = \pm H_{x,ext}$ which give the $R_{PHE}$.

The measurements were carried out in the wires with stacks of Ta(t nm)/Co(2 nm)/Pt(5 nm), where $t = 4, 6, 8$ and 10 nm. The fabrication and patterning processes of the wires are described elsewhere20-22. The SOT fields are quantified as a function of the longitudinal fields in the sample of Ta(4 nm)/Co(2 nm)/Pt(5 nm). In this quantification, the constant longitudinal field $H_{x,ext}$ was applied in a range of 250 Oe to 650 Oe with a 50 Oe increment.

For each value of $H_{x,ext}$, the ratio of the maximum value of the sweeping field $H_{x,ext}$ to $H_{x,ext}$ was fixed. An AC frequency of 307.1 Hz was used for the low-frequency harmonic Hall resistance measurements. The amplitudes of the AC current were in the range of $3 \times 10^{-10}$ to $10^{10}$ Am$^{-2}$ with an increment of $10^{8}$ Am$^{-2}$. The first and second harmonic Hall resistances were measured using a 7265 DSP lock-in amplifier. The obtained harmonic Hall resistances at applied fields $H_{x,ext} = 250$ Oe, 450 Oe, and 650 Oe and current density of $1 \times 10^{11}$ Am$^{-2}$ are shown in Fig. 1.

The measured first harmonic Hall resistances $R_{1st Hall}$ exhibit typical $\sin 2\phi_0$ behaviors as functions of the azimuthal angle $\phi_0$ of the magnetization, and the minimum and maximum values of $R_{1st Hall}$ are at $\phi_0 = \pm 45$ degrees. Correspondingly, for each value of $H_{x,ext}$, shown in the inset of Fig. 1(a), the minimum and maximum values of $R_{1st Hall}$ occur at $H_{y,ext} = \pm H_{x,ext}$, which give the values of $R_{PHE}$ and the ratio of $R_{PHE}/H_{x,ext}$ shown in Fig. 1(b). In Fig. 1(c), the measured second harmonic Hall resistances, $R_{2ndHall}$, are shown to increase with increasing $X$ for each value of $H_{x,ext}$. Fitting the experimental $R_{2nd Hall}$ by Eq. (1), where the values of $R_{PHE}$ and $R_{1st Hall}/H_{x,ext}$ are recorded in Fig. 1(b), we compute the two effective SOT fields, $H_{D}$ and $H_{F}$.

As shown in Fig. 2, for each value of $H_{x,ext}$, $H_{D}$ and $H_{F}$ increase with respect to the current density at each value of $H_{x,ext}$. The values of $H_{D}$ and $H_{F}$ are similar to that reported in the same stack20. We notice that $H_{D}$ and $H_{F}$ vary with the longitudinal field for each value of the applied current densities. However, at the current density of $3 \times 10^{10}$ Am$^{-2}$, the field-like term variation is 19.7%, and the damping-like term variation is 16.9% when $H_{x,ext}$ increases from 250 Oe to 650 Oe. At the current density of $10^{11}$ Am$^{-2}$, the field-like term variation increases to 21.5% and the damping-like term variation decrease to 12.4%. The variations are not only the functions of the magnetization uniformity but also the applied current. The role of the current in the variation indicates that possible thermal effect, such as the anomalous Nernst effect, should exist during the SOT measurement23-26. Due to Joule heating which is induced by electric current, the different resistances give rise to a thermal gradient along the normal direction of the stack. The thermal gradient contributes to the measured second harmonic Hall resistances which were used to calculate the SOT effective fields43. Depending on the direction of the thermal gradient; the thermal contribution may lead to an over or underestimation of the SOT effective field when the current density increases. However, in our measurement regime, the thermal effects are considered negligible because the current density in our experiments was in the range of $\sim 10^5$ A/m$^2$, where Joule heating is generally negligible4. Furthermore, both the damping like term and field like term relates monotonically with the applied current density as shown in Fig. 2, implying that the thermal effects insignificantly to the SOT effective field27-28.

The magnetization uniformity is equivalent to magnetization amplitude $M$ for the magnetic wire. This magnetization amplitude can be characterized with respect to the applied longitudinal field by measuring $R_{1st Hall}$ thereby obtaining the $R_{PHE}$. As shown in Fig. 1(b), $R_{PHE}$ increases with respect to $H_{x,ext}$, where $H_{x,ext}$ is extended to 100 Oe. This increase is attributed to the polycrystalline structure of the Co layer in the sputtered Ta/Co/Pt film. Without applying $H_{x,ext}$, the magnetic moment of Co crystalline grains orients randomly in the film. This is due to the random orientation of the effective field $H_{e,ext}$ generated by the crystalline magnetic anisotropy of each grain. Hence, the $M$ of the wire equals the value of remanence magnetization $M_r$ which is determined by the intrinsic demagnetizing field transverse to the wire.

However, when $H_{x,ext}$ is applied, the magnetic moment $m$ of the grains re-orients towards the x-axis, as schematically shown in Fig. 3(a). Consequently, $M$ increases starting from $M_r$. The increase of $M$ leads to the
increase of $R_{\text{PHE}}$, as $M$ is related to $R_{\text{PHE}}$ by the expression $R_{\text{PHE}} = kM^2$ \cite{29-31}, where $k$ is a material related coefficient. The maximum of $M$ is the saturation magnetization $M_s$. Therefore, $M_H$, defined as $M_H = M_s - M_r$, is the maximum of the magnetization component, which can be manipulated by the external field $H_{x\text{-}ext}$. We consider the magnetization component as the resultant of two vectors expressed by $M_H/2$, instead of evaluating the contribution from each magnetic grain to the magnetization component. As shown in Fig. 3(b), $H_{x\text{-}ext}$ orientates both vectors along the x-axis, while the nonzero y component $H_{y\text{crys}}$ of $H_{\text{crys}}$ orientates each vector along the $\pm y$ direction, respectively. Hence, each $M_H/2$ orientates at their balanced direction determined by $H_{x\text{-}ext}$ and $H_{y\text{crys}}$, as shown in Fig. 3(b). The y components of the two vectors cancel each other, while the x component of each vector.

Figure 1. (a) The measured first harmonic resistances $R_{\text{1st Hall}}$ with respect to the azimuthal angle $\phi_0$ of magnetization. Inset is the measured $R_{\text{1st Hall}}$ with respect to the applied transverse field $H_{y\text{-}ext}$. (b) The measured $R_{\text{PHE}}$ and the calculated $M$, with respect to the longitudinal field. $R_{\text{PHE}}$ is obtained by fitting the sin$^2\phi_0$ curves of (a). (c) The measured second harmonic Hall resistances $R_{\text{2nd Hall}}$ with respect to the cosine $X$ of the azimuthal angle. Inset is the measured $R_{\text{2nd Hall}}$ with respect to applied transverse field $H_{y\text{-}ext}$.

Figure 2. The measured field-like term (a), and damping-like term (b), with respect to the longitudinal field.
Figure 3. (a) The schematic of a polycrystalline magnetic structure and the orientation of magnetic moment for each of crystalline grain under \( H_{x,ext} \) and transverse demagnetizing field. (b) The schematic of the magnetization composition for the magnetic structure.

The SOT effective fields per 10\(^{11}\) Am\(^{-2}\) at each value of \( H_{x,ext} \) were obtained from Fig. 2, for comparison. Replacing \( H_{x,ext} \) with the corresponding value of \( M \) shown in Fig. 1(b), the SOT effective fields per 10\(^{11}\) Am\(^{-2}\) with respect to \( M \) are plotted for sample Ta (4 nm)/Co (2 nm)/Pt (5 nm) in Fig. 4. Similarly, the SOT effective fields per 10\(^{11}\) Am\(^{-2}\) and the magnetization were quantified for samples Ta (4 nm)/Co (2 nm)/Pt (5 nm), where \( t = 6, 8 \) and 10. As reported previously\(^{39}\), similar saturation magnetization values for the samples \( t_{a} = 4 \) nm and \( t_{a} = 8 \) nm leads to similar tendencies of the field like and damping like fields due to their dependence on magnetization. While substantial differences in the saturation magnetization values for samples \( t_{a} = 6 \) nm and \( t_{a} = 8 \) nm leads to different tendencies of the field-like and damping like SOT fields. As shown in Fig. 4(a,b), the field-like term decreases with respect to the magnetization magnitude while the damping-like term increases in each sample.

We demonstrate that the dependence of the SOT effective fields on the magnetization magnitude or uniformity is attributed to SHE in the Ta/Co/Pt structure. SHE-induced spin accumulation, \( s \), which is at the interfaces of Ta/Co and Co/Pt, diffuses into the FM layer to cause STT on the magnetization\(^3\). In the STT model proposed by S. Zhang\(^{39}\), the spin current, which is from a reference layer, leads to transverse spin accumulation in the free layer. Consequently, the transverse spin accumulation induces two effective fields: \( b\mathbf{m} \) and \( a\mathbf{m} \times \mathbf{m} \), where \( \mathbf{m} \) and \( \mathbf{m} \) are unit vectors of the local magnetization of the reference layer and the free layer, respectively. When \( \mathbf{m} \) and \( \mathbf{m} \) are in the planes of the magnetic layers, \( b \) and \( a \) are expressed as \( b = (h_{f} / \varepsilon M_{f,t}) \sin \xi \cdot e^{-z} \) and \( a = (h_{f} / \varepsilon M_{f,t}) (1 - \cos \xi \cdot e^{-z}) \), respectively, where \( h \) is the Planck constant, \( j_{f} \) is the electric current density perpendicular to the plane of magnetic layers, \( t_{f} \) is the thickness of the free layer, and \( e \) is the electron charge. In the expressions of \( b \) and \( a \), \( \xi \) equals to \( \xi / 2 \lambda \) with a spin diffusion length \( \lambda = \sqrt{2 h D_{\varphi} / j_{f}} \), where \( j_{f} \) is a coefficient of the contact interaction between the spin accumulation and the local magnetization of the free layer, and \( D_{\varphi} \) is the electron diffusion constant. Analogously in the Ta/Co/Pt structure, the Ta or Pt layer is used to generate spin current normal to the magnetic Co layer. Hence, the Ta or Pt layer is similar to the reference layer, as such, \( s \) can be considered as \( b\mathbf{m} \). The spins generated by the Ta and Pt layers are accumulated at the Co layer, which allows us to take the Co layer as analogous to the free layer. Similarly, \( \mathbf{m} \) is to \( \mathbf{m} \). Consequently, the field-like term, \( H_{F} \), is equivalent to \( b\mathbf{m} \), and the damping-like term, \( H_{D} \), is equivalent to \( a\mathbf{m} \times \mathbf{m} \). Thus, we obtain \( H_{F} = (h_{f} / \varepsilon M_{f,t}) (\sin \xi \cdot e^{-z}) \) and \( H_{D} = (h_{f} / \varepsilon M_{f,t}) (1 - \cos \xi \cdot e^{-z}) \) for the Ta/Co/Pt samples, where \( j_{f} \) is the charge current.
We propose that the magnetization magnitude of Co layer manipulate the SOT effective fields via the coefficient $\xi$, considering the above expressions of $H_F$ and $H_D$. The damping-like term is related to spin Hall angle $\theta_{SH}$ via the expression $H_D = \theta_{SH} hJ_e / eM_{st} t_F$, where $\theta_{SH}$ is defined as the ratio of spin current $j_s$ to charge current $j_e$. Comparing the two expressions of $H_D$, we obtain $\theta \xi = -\xi + e \cos \theta_{SH}$. As such, $\xi$ is $\leq 1.6$, since the sum of Pt and Ta spin Hall angles is $\leq 17,36$. As $\xi \lambda = t/(2\lambda) F J$, and $\lambda$ is about 1.2~2.4 nm for Co, we obtain $\xi \geq 0.6$, using the Co layer thickness $t_F = 2$ nm. Therefore, our samples have values of $0.6 \leq \xi \leq 1.6$. $\xi$ can be rewritten as $\xi = (t_F/2) \sqrt{hJ_0}$, where $J_0$ is related to the magnetization of the wire. Ustinov created a superlattice model to explain the correlation of $D_0$-related magnetoresistance (MR) and magnetization. In this model, the superlattice comprises of several magnetic layers, and for any of two adjacent layers, magnetizations are initially antiparallel to each other. A transverse magnetic field, which is perpendicular to the initial magnetization in the plane of the magnetic layers, is applied to change the magnetization amplitude of the superlattice. The model concludes that the MR increases with respect to the magnetization of the superlattice. Hence, $D_0$ decreases with increasing magnetization in our samples, as it is inverse proportional to MR. Therefore, $\xi$ increases with respect to the magnetization magnitude, due to $\xi = (t_F/2)/(\sqrt{hJ_0})$. In the range of 0.6~1.6 for our samples, the increase of $\xi$ leads to the decrease of the term $\sin \xi e^{-\xi}$ and increase of the term $1 - \cos \xi e^{-\xi}$, as shown in Fig. 4(c). Therefore, $H_F$ decreases and $H_D$ increases with respect to the magnetization, respectively, as the term $hJ_e / eM_{st} t_F$ is a constant for each sample.

**Conclusion**

In conclusion, our measurement results show that the SOT effective fields depend on the magnetization uniformity in Ta/Co/Pt structure. The dependence indicates that the SOT effective fields can be manipulated by varying the magnetization uniformity. The change of magnetization uniformity was achieved in each sample by applying magnetic fields along the long axis of the wire. As the SOT effective fields are concurrently characterized, our characterization method eliminates influences from other SOT dependence effects. As an analogy to the STT effect from a reference layer, the SOT dependence on the magnetization uniformity is attributed to the electron diffusion properties. This dependence suggests that SHE plays a significant role in the dependence of SOT effective fields on magnetization. It also indicates that the SOT effective fields cannot be considered as constant.
parameters when analyzing domain wall dynamics via SOT. Moreover, we conclude that magnetization enhances the damping-like torque while suppressing the field-like torque.

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Author Contributions
F.L. Luo carried out the experiments. S.H. Li, F.N. Tan, and G.J. Lim assisted in the thin film deposition and electron beam patterning. F.L. Luo, Q.Y. Wong, and W.S. Lew prepared the figures and the main manuscript. All authors discussed the data and the results and commented on the manuscript. W.S. Lew supervised the project.

Additional Information
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