Spin-orbit torque (SOT) effective fields and SOT-induced switching in perpendicularly magnetized multilayers

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**NANYANG
TECHNOLOGICAL
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SINGAPORE

**SPIN-ORBIT TORQUE (SOT) EFFECTIVE FIELDS AND SOT-
INDUCED SWITCHING IN PERPENDICULARLY
MAGNETIZED MULTILAYERS**

SIHUA LI

SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES

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SIHUA LI

SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES

A thesis submitted to the Nanyang Technological
University in partial fulfilment of the requirement for the
degree of Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research done by me except where otherwise stated in this thesis. The thesis work has not been submitted for a degree or professional qualification to any other university or institution. I declare that this thesis is written by myself and is free of plagiarism and of sufficient grammatical clarity to be examined. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

This thesis contains material from 2 papers published in the following peer-reviewed journals where I was the first and/or corresponding author.

Chapter 3 is published as S. Li, G. Lim, W. Gan, W. Law, F. Tan, and W. S. Lew. Tuning the spin-orbit torque effective fields by varying Pt insertion layer thickness in perpendicularly magnetized Pt/Co/Pt(t)/Ta structures. *Journal of Magnetism and Magnetic Materials* **473**, 394 (2019). DOI: 10.1016/j.jmmm.2018.10.104.

The contributions of the co-authors are as follows:

- I designed the project. I fabricated the samples and collected the scanning electron microscopy images. I carried out the Hall resistance measurements and harmonic Hall voltage measurements, with conducted data evaluation. I also analyzed the data and prepared the manuscript drafts. The manuscript is revised by all listed authors.
- Gerard and Funan deposited the thin films and assisted in ion milling in the fabrication process.
- Weiliang suggested in the interpretation of data and writing in the manuscript.
- Wai Cheung provided film characterization data.
- The project is supervised by Prof. Lew.

Chapter 5 is published as S. Li, S. Goolaup, J. Kwon, F. Luo, C. Engel, W. Gan, and W. S. Lew. Deterministic spin orbit torque induced magnetization reversal in Pt/[Co/Ni]₂/Ta structure. *Scientific Reports* 7, 972(2017). DOI:10.1038/s41598-017-01079-7.

The contributions of the co-authors are as follows:

- Dr. Goolaup the initialized the experiments.
- I co-designed the experiments with Dr. Goolaup. I fabricated the samples and carried out all the experimental measurements. I also analyzed the data and prepared the manuscript drafts with the assistant of Dr. Goolaup.
- Dr. Kwon, Feilong and Christian assisted in conducting the harmonic Hall voltage measurements. They also provided guidance in the interpretation of the measurement data.
- Weiliang assisted in the collection and analysis of data from the Kerr imaging.
- Prof. Lew supervised the project.

16/01/2019

Date

Sihua Li

Abstract

Spin-orbit torque (SOT) is an electrical-driven phenomenon in which the magnetization of a ferromagnetic material can be switched by the momentum transfer of the diffused accumulated spins at the heavy metal (HM)/ferromagnet (FM) interface, when applying an electric current through the HM layer. The SOT effect is highly attractive from application viewpoint, specifically for faster magnetization switching and lower power non-volatile memory devices. However, the search for in-depth physics understanding of the SOT continues, specifically on the SOT-induced magnetization switching phenomenon. In this thesis, systematic investigation of the physics governing the SOT-induced magnetization switching has been carried out by examining the SOT effective fields, *i.e.*, damping-like term and field-like term. AC harmonic Hall voltage measurement technique was applied to characterize the SOT effective fields in Pt/Co/Ta structure with perpendicular magnetic anisotropy (PMA). It is found that the sign and magnitude of the damping-like term are dependent on the thickness of the inserted Pt layer at the Co/Ta interface, while that is negligible for the field-like term. In the Pt/Co/Pt/Co/Ta structure, the effective field strength is dependent on the lower Co layer thickness while no changes were observed with varying upper Co layer thickness. The asymmetric dependence of the SOT on the two Co layer thicknesses is attributed to the modulations of the saturation magnetization as a result of their different interface conditions. Additionally, by exploiting the intrinsic tilt of the magnetization in the Pt/[Co/Ni]₂/Co/Ta structure, it is shown that field-free SOT-induced magnetization switching is possible. Kerr imaging reveals that the field-free SOT switching process is completed via the nucleation of reverse domain and propagation of domain wall in the system.

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List of abbreviations

MRAM	Magnetoresistive random access memory
DW	Domain-wall
MTJ	Magnetic tunnel junction
STT	Spin-transfer torque
SOT	Spin-orbit torque
CMOS	Complementary metal oxide semiconductor
GMR	Giant magnetoresistance
PMA	Perpendicular magnetic anisotropy
FM	Ferromagnetic metal
HM	Heavy metal
SHE	Spin Hall effect
LLG	Landau–Lifshitz–Gilbert
VSM	Vibrating sample magnetometer
SEM	Scanning electron microscopy
MOKE	Magneto-optical Kerr effect
AHE	Anomalous Hall effect
PHE	Planar Hall effect
AC	Alternating current
DC	Direct current
SOC	Spin-orbit coupling
EBL	Electron beam lithography
DL	Damping-like
FL	Field-like

List of publications

Journal publications

1. *"Tuning the spin-orbit torque effective fields by varying Pt insertion layer thickness in perpendicularly magnetized Pt/Co/Pt(t)/Ta structures"*

Sihua Li, Gerard Joseph Lim, Weiliang Gan, Wai Cheung Law, Funan Tan, Wen Siang Lew

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2. *"Deterministic spin orbit torque induced magnetization reversal in Pt/[Co/Ni]₂/Ta structure"*

Sihua Li, Sarjoosing Goolaup, Jaesuk Kwon, Feilong Luo, Christian Engel, Weiliang Gan, Wen Siang Lew

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3. *"An Artificial Skyrmion Platform with Robust Tunability in Synthetic Antiferromagnetic Multilayers"*

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4. *"Asymmetric Co layer thickness dependence of spin-orbit torque in Pt/Co/Pt/Co/Ta structures with perpendicular magnetic anisotropy"*

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5. *"Dependence of spin-orbit torque effective fields on the magnetization azimuthal angle in Ta/Co/Pt stack"*

Feilong Luo, Sarjoosing Goolaup, Christian Engel, **Sihua Li**, Funan Tan, Gerard Joseph Lim, W.S. Lew

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6. *"Electric field control for energy efficient domain wall injection"*

Funan Tan, Qi Ying Wong, Weiliang Gan, **Sihua Li**, H.X. Liu, F. Poh, Wen Siang Lew

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7. *"Simultaneous determination of effective spin-orbit torque fields in magnetic structures with in-plane anisotropy"*

Feilong Luo, Sarjoosing Goolaup, Wai Cheung Law, **Sihua Li**, Funan Tan, Christian Engel, Tiejun Zhou, Wen Siang Lew

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8. *"Characterizing the spin orbit torque field-like term in in-plane magnetic system using transverse field"*

Feilong Luo, Sarjoosing Goolaup, **Sihua Li**, Gerard Joseph Lim, Funan Tan, Christian Engel, Senfu Zhang, Fusheng Ma, Tiejun Zhou, Wen Siang Lew

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9. *"Modulation of spin-orbit torque efficiency by thickness control of heavy metal layers in Co/Pt multilayers "*,

Pankaj Sethi, Sachin Krishnia, **Sihua Li**, Wen Siang Lew

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Conference publications

1. “Chiral magnetization switching induced by spin orbit torque in Pt/Co/Ta structure”

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2. “The effect of inserting a Pt layer in Pt/Co/Ta structure on spin orbit torque”

Sihua Li, Gerard Joseph Lim, Wen Siang Lew

INTERMAG 2018, Singapore

3. “Spin Hall effect induced SOT fields in perpendicular magnetized Co/Ni multilayer systems”

Sihua Li, Sarjoosing Goolaup, Feilong Luo, Wen Siang Lew

INTERMAG 2017, Dublin, Ireland

4. “Giant damping-like spin orbit torque in perpendicular magnetized double Pt/Co stack structure”

Sihua Li, Sarjoosing Goolaup, Wen Siang Lew

INTERMAG 2017, Dublin, Ireland

5. “SOT-induced magnetization reversal in Pt/[Co/Ni]₂/Co/Ta multilayer Hall bars without external magnetic field”

Sihua Li, Sarjoosing Goolaup, Weiliang Gan, Wen Siang Lew

INTERMAG 2017, Dublin, Ireland

Chapter 1. Introduction

Conventional microelectronic devices based on the transition of electron charge have been widely applied in human life. The studies on spin, another inherent attribute of electron, find that electron spin has more advantages than electron charge in the last several decades. Attempts to use both charge and spin of electron have given rise to an emerging field known as spintronics. The electron spin denoted by one of its two possible states on arbitrary axis has huge potential in digital information processing. The energy to reverse the spin orientation is amazingly small, which opens great opportunities to reduce the power consumption of electronic circuits for future devices. Recently, the spintronic devices are proposed to be strong candidates in memory technology owing to its advantages of non-volatility and compatibility with CMOS circuits, especially magneto-resistive devices constructed by a magnetic tunnel junction (MTJ) structure. The discovery of spin-transfer torque (STT) effect promises the possibility of directly magnetization via charge current, which builds new spin-based devices for integrating data storage and data processing techniques, such as spin transfer torque magnetic random-access memory (STT-MRAM). Lately, a new transport effect named spin-orbit torque (SOT) has attracted intense interest of research. It has been

perceived as a better alternative to invert the magnetic moments in memory devices, due to its higher power efficiency than STT. Though many investigations of SOT have been reported, the in-depth understanding of physics of SOT is still under debate. In the thesis, my research focuses on the quantification of the SOT effective fields and investigation of SOT-induced magnetization switching in magnetic multilayers with perpendicular magnetic anisotropy. The related fundamentals are included in this chapter, and the last section of this chapter describes the structure of the thesis.

1.1 Spin of electron and spin-orbit coupling

As a fundamental particle, electron is proved to exist objectively by Thomson in 1897 [1, 2]. It possesses one elementary negative charge, which promises the application of electronic devices based on manipulating electron charge [3]. The invention of evacuated tube [4] and transistor [5] makes the electronic devices possible to be widely applied in human life. With the further understanding of electron, the spin of electron is discovered [6], and it can be controlled to implement various functions, which facilitates the development of spintronic devices [7]. The advantages of miniaturization and low power consumption make the spintronic devices the focus of research [8-10].

In 1922, Stern and Gerlach experimentally discovered the spin of electron [6], as the electron moves along its orbit of an atom. Both motion and spin are intrinsic properties of electron, associated with the intrinsic form of angular momentum in quantum mechanics. The former generates an orbital angular momentum, which has the same relationship as classical definition

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}. \quad (1-1)$$

Here, $\mathbf{r}$ is the position operator, $\mathbf{p}$ is the momentum operator, and $\mathbf{L}$ is the orbital angular momentum operator. The latter produces another type of angular momentum, called spin angular momentum (usually denoted $\mathbf{S}$). As a quantum concept, spin is quantized with a spin quantum number $s = \frac{1}{2}$, resulting in a constant magnitude of spin angular momentum

$$S = \hbar\sqrt{s(s+1)} = \frac{\sqrt{3}}{2}\hbar. \quad (1-2)$$

Its component along the arbitrary z-axis (usually determined by an external magnetic field) is given by $S_z = m_s \cdot \hbar$. The electron spin can be denoted by either an upward ($m_s = +\frac{1}{2}$) arrow or a downward ($m_s = -\frac{1}{2}$) arrow, as shown in Figure 1-1.

Figure 1-1. Illustration of spin "up" and "down".

The total angular momentum $\mathbf{J}$, which combines both the spin and orbital angular momentums, is given by

$$S \cdot L = \hbar\sqrt{s(s+1)}L = \frac{\sqrt{3}}{2}\hbar L. \quad (1-3)$$

The spin angular momentum of electron can interact with its orbital angular momentum, due to the relativistic interaction of electron spin with its motion inside a potential, known as spin-orbit coupling (SOC) [11-13]. SOC makes it possible that $\mathbf{L}$ and $\mathbf{S}$ are not conserved, while the total $\mathbf{J}$ remains conserved. For a monovalent atom, the Hamiltonian of the valence electron without external magnetic fields can be written as

$$H_0 = \frac{p^2}{2m_e} + V(r) + \xi(r)\mathbf{S} \cdot \mathbf{L}. \quad (1-4)$$

The last term is the SOC energy. The applied magnetic field can generate a magnetic potential

$$H' = -\mathbf{B} \cdot (\boldsymbol{\mu}_l + \boldsymbol{\mu}_e) = \frac{eB}{2m_e c} (L_z + 2S_z). \quad (1-5)$$

The total Hamiltonian of the valence electron becomes

$$H = H_0 + H'. \quad (1-6)$$

In case of weak magnetic field, the magnetic potential is smaller than the SOC energy, which makes H' a perturbation. Taking (H_0, L^2, J^2, J_z) as common eigenfunction, the zero-order approximation of wave function can be written as

$$\Psi_{nljm_j}^{(0)} = R_{nl}(r)\psi_{ljm_j}(\theta, \varphi, S_z), \quad (1-7)$$

where $\psi_{ljm_j}(\theta, \varphi, S_z)$ represents the common eigenfunction of (L^2, J^2, J_z) . The eigenvalue of H_0 is the energy level of the valence electron, and it depends on the quantum number n, l, j , being independent on m_j . It can be recorded as $E_{nlj}^{(0)}$, whose degeneracy of energy level is $2j+1$. For given values of n and l , $j = l \pm \frac{1}{2}$ corresponds to two energy levels, describing the fine structure of energy level.

According to the degenerate state perturbation theory [12], the first-order correction of energy attributed to the magnetic potential H' can be obtained as

$$E_{nljm_j}^{(1)} = \int (\Psi_{nljm_j}^{(0)} + H' \Psi_{nljm_j}^{(0)}) d\tau = \frac{eB}{2m_e c} (J_z + S_z) = \frac{eB}{2m_e c} (m_j \hbar + \frac{\hbar}{2} \sigma_z). \quad (1-8)$$

σ_z can be solved from the equation

$$\boldsymbol{\sigma}(\boldsymbol{\sigma} \cdot \mathbf{L}) + (\boldsymbol{\sigma} \cdot \mathbf{L})\boldsymbol{\sigma} = 2\mathbf{L}. \quad (1-9)$$

Averaging the equation (1-9) under the state of Ψ_{nljm_j} , can obtain

$$\langle \boldsymbol{\sigma} \rangle (\boldsymbol{\sigma} \cdot \mathbf{L}) = \langle \mathbf{L} \rangle, \quad (1-10)$$

where $(\boldsymbol{\sigma} \cdot \mathbf{L})$ becomes the eigenvalue.

Due to $\mathbf{J} = \mathbf{L} + \frac{\hbar}{2} \boldsymbol{\sigma}$, the equation (1-10) can be written as

$$\langle \boldsymbol{\sigma} \rangle \left(\frac{\hbar}{2} + \boldsymbol{\sigma} \cdot \mathbf{L} \right) = \langle \mathbf{J} \rangle. \quad (1-11)$$

Under the eigen state of $\mathbf{J}_z$, $\langle \mathbf{J}_x \rangle = \langle \mathbf{J}_y \rangle = 0$, result in $\langle \boldsymbol{\sigma}_x \rangle = \langle \boldsymbol{\sigma}_y \rangle = 0$. It is also given that

$$\frac{\hbar}{2} + \boldsymbol{\sigma} \cdot \mathbf{L} = \begin{cases} (l+\frac{1}{2})\hbar & j=l+\frac{1}{2} \\ -(l+\frac{1}{2})\hbar & j=l-\frac{1}{2} \end{cases} = \begin{cases} j\hbar, & j=l+\frac{1}{2} \\ -(j+1)\hbar, & j=l-\frac{1}{2} \end{cases}. \quad (1-12)$$

Substituting equation (1-12) into equation (1-11), we can obtain

$$\langle \boldsymbol{\sigma} \rangle = \begin{cases} \frac{m_j}{j}, & j=l+\frac{1}{2} \\ -\frac{m_j}{j+1}, & j=l-\frac{1}{2} \end{cases}. \quad (1-13)$$

Substituting equation (1-13) into equation (1-8), the first-order correction of energy is acquired as

$$E_{nljm_j}^{(1)} = B\mu_B m_j g. \quad (1-14)$$

Here, g is the Landé factor, which is expressed by

$$g = 1 + \frac{\langle \mathbf{S}_z \rangle}{2m_j} = 1 + \frac{\langle \mathbf{S}_z \rangle}{\langle \mathbf{J}_z \rangle} = \begin{cases} 1 + \frac{1}{2j}, & j = l + \frac{1}{2} \\ 1 - \frac{1}{2(j+1)}, & j = l - \frac{1}{2} \end{cases}. \quad (1-15)$$

The combination of equations (1-14) and (1-15) gives the result that the energy level $E_{nlj}^{(0)}$ is split into $(2j+1)$ energy levels with equal interval in weak magnetic field, corresponding to the $(2j+1)$ values of m_j ,

$$m_j = j, j-1, \dots, (-j). \quad (1-16)$$

The energy level spacing is $B\mu_B g$. In simple Zeeman effect, the spacing of split energy levels is $B\mu_B$. The energy level transition of valence electron occurs following the selection rule

$$\Delta l = \pm 1; \Delta j = 0, \pm 1; \Delta m_j = 0, \pm 1; \quad (1-17)$$

which generates its spectrum. The SOC of electrons involved with both spin and motion has played a significant role in various technological applications in semiconductor industry.

According to relativistic effects, an electron moving in a noncollinear electric field will experience an effective magnetic field, which is written as

$$\mathbf{B} = \frac{-1}{c} \mathbf{v} \times \mathbf{E}, \quad (1-18)$$

where $\mathbf{v}$ is the velocity of electron and $\mathbf{E}$ is the electric field. The SOC can be understood by the electromagnetic interaction between the magnetic moment of an electron and the effective magnetic field produced by the electron's orbital motion. The interaction energy is expressed by

$$E_{SO} = -\mu_s \cdot B = \frac{\mu_o Z e^2}{4\pi m_e^2 r^3} (\mathbf{S} \cdot \mathbf{L}). \quad (1-19)$$

It suggests an additional contribution to the Hamiltonian of an atom in Eq. (1-4) caused by SOC.

1.2 Introduction to ferromagnetic metals, Fe, Co, Ni

Magnetism of material origins from the atomic magnetic moment, containing the orbital and spin magnetic moments of electrons. They are sorted into three types of weak magnetism and two types of strong magnetism in practical view. Most materials do not show macroscopic magnetism due to the chaotic directions of atomic magnetic moments, though the inherent magnetic moment of an atom exists. These materials are known as paramagnets. Another two types of weak magnetism are diamagnetism and anti-ferromagnetism. The former has a negative magnetic susceptibility with very small absolute value. In antiferromagnet, spin is arranged in antiparallel by sub-lattice with magnetic moments of the same magnitude and opposite orientations, which results in that the macroscopic magnetism of antiferromagnet equals zero. Totally different with the previous three types of magnetism, the inner atomic magnetic moment of ferromagnet is spontaneously arranged in parallel by region, exhibiting a strong magnetism. As the last type of magnetism, ferrimagnet has the same inner magnetic structure as the antiferromagnet, while the different amounts of magnetic moment arranged in antiparallel lead to a strong magnetism.

The spin-dependent conduction in ferromagnetic metals lead to the discovery of the giant magnetoresistance (GMR), which makes it possible to simultaneously regulate and control both charge and spin of electrons. As a historic breakthrough, the GMR effect has promoted the development of emerging spintronics, which is different from the traditional electronics and microelectronics where only the electron charge is used.

1.2.1 Origin of ferromagnetism

In case of an electron revolving around a nucleus, the motion of electron charge forms a circular current and induces a magnetic field [15, 16]. The orbital magnetic moment generated by the circular current is in line with the orbital angular momentum of the electron and their directions are opposite. For polyelectronic atoms, the electron configuration observes two rules, Pauli exclusion principle and minimum energy principle. The state of an electron is determined by four quantum numbers, n , l , j , m_j . Both the total angular momentum and magnetic moment of full electronic shell equal zero. Only the unpaired electronic magnetic moment in unfilled shell of electrons can contribute to the total magnetic moment of atoms.

In the periodic table of elements, the elements in iron family, i. e., Fe, Co, Ni, possess the strongest magnetism, widely used in various magnetic technology and life as ferromagnets. The magnetic moments in these metals are almost entirely contributed by $3d$ electrons. It is experimentally found that the orbital magnetic moment in them is too small to contribute to the total magnetic moment, due to the freezing of orbital angular momentum [16, 17]. Consequently, the spin magnetic moment of $3d$ electrons makes entire contributions to their magnetism. The exchange interaction of $3d$ electrons leads to that the electrons with parallel spins have lower energy than the electrons with antiparallel spins. To reduce the total energy, some negative spins are transferred to positive spins. The unequal numbers of electrons with positive spins and negative spins induce the spontaneous magnetization of ferromagnetic metals.

Figure 1-2. Schematic diagram of electronic density of energy state in Fe, Co and Ni, including both $3d$ and $4s$ bands. The average numbers of electrons in each spin state which is described by the white arrows. The blue indicates “majority spins” which have more electrons, and the red indicates “minority spins” which have less electrons, in $3d$ bands.

An energy band model, named Stoner-model, can be used to demonstrate the contribution from the spin of $3d$ electrons, as shown in Figure 1-2. Figure 1-2 displays the schematic diagram of electronic density of energy state in Fe, Co and Ni [17-20]. It is observed that $4s$ electrons have the same amounts of electrons in spin “up” and spin “down” states [16, 17], which contribute a magnetic moment of $+\mu_B$ and $-\mu_B$, respectively. (The $4s$ band whose width is around 10 eV, is filled with both the $4s$ electrons and $4p$ electrons. However, only $4s$ electrons are considered here to relate to the classical atom configuration. For further information, please refer to page 523 in Ref. [17] and Chapter 3 in Ref. [16]). The magnetic moments contributed by the “up” and spin “down” $4s$ electrons approximately counteract each other, result in a zero contribution to the total magnetic moment (The little contribution with numerical value can be referred in page 527 in Ref. [17]).

As shown in Figure 1-2, the $3d$ energy band has an asymmetric structure with the band width of about 3 eV [16, 17], since that the exchange interactions (~ 1 eV) of $3d$

electrons split off the energy band [16, 20]. Consequently, the numbers of the $3d$ electrons with magnetic moment of $+\mu_B$ (n_+) and $-\mu_B$ (n_-) become unequal. The net number defined as $\Delta n = n_+ - n_-$, contributes to the total magnetic moment of an atom as $m_a = \mu_B \Delta n$. Δn is experimentally quantified to be around 2.2, 1.7, and 0.6 for Fe, Co, and Ni, and gives the corresponding magnetic moment of an atom as about $2.2 \mu_B$, $1.7 \mu_B$, and $0.6 \mu_B$, respectively [17]. For the bulk magnetic materials, the saturation magnetization determined by the magnetic moment of the atoms at the temperature of 0 K, is generally used to characterize the magnetism. As an experimental result, the saturation magnetizations of 2.2 T (1751 emu/cc), 1.8 T (1432 emu/cc), and 0.7 T (557 emu/cc) for bulk Fe, Co, and Ni are obtained at the temperature of 4.2 K [17]. The comparison of the saturation magnetization at the temperature of 4.2 K with Δn , implies that the number of the saturation magnetization in unit of T gives an estimated number of $3d$ electrons generating the magnetism of an atom in ferromagnets [18].

1.2.2 Two-current model in spin-dependent conduction in ferromagnet

For transition metals, $3d$ and $4s$ bands have the same Fermi energy and Fermi surface. Both $3d$ and $4s$ electrons near the Fermi surface participate in conducting. The mobility of $4s$ electrons in electric field is much larger than $3d$ electrons, as $4s$ electrons can flow much faster than $3d$ electrons. Though the amount of $3d$ electrons is greater than that of $4s$ electrons in transition metals, the electric conduction is mainly via $4s$ electrons.

In normal metals and paramagnetic metals, the conductivity is independent of spin, which is the known cases. Figure 1-2 demonstrates the principle of the electric

conduction in ferromagnetic metals, which is spin-dependent [21]. The resistivity of ferromagnetic metals is expressed by

$$\rho_{\sigma} = m_{\sigma}^* / n_{\sigma} e^2 \tau_{\sigma}, \quad (1-20)$$

where m_{σ}^* is effective mass of conduction electron, n_{σ} is the electronic density at Fermi surface, and τ_{σ} is the relaxation time of electron scattering. Describing the magnitude of scattering probability, τ_{σ} is proportional to the mean free path of electron motion λ_{σ} , which is expressed by

$$\tau_{\sigma} \sim \lambda_{\sigma} \sim 1/|V_{\sigma}|^2 N_{\sigma}(E_F), \quad (1-21)$$

where V_{σ} is the element of scattering potential matrix causing the electron scattering, and $N_{\sigma}(E_F)$ is the density of energy states at Fermi surface related to the final state of scattering. σ represents spin “up” or “down”, in expression of $\sigma = \uparrow, \downarrow$. $\uparrow$ is defined as the spin direction parallel to magnetization, which is the same as the orientation of “minority spins” or spontaneous magnetization. $\downarrow$ represents the direction of “minority spins”. The related physical quantities with subscript σ in equations (1-20) and (1-21) imply that they are spin-dependent, leading to the spin-dependent conduction in ferromagnetic metals. The phenomenon of different amounts of conduction electrons with “up” and “down” spins is called the spin polarization of electron flow, which is one of the three mechanisms behind the spin-dependent conduction in ferromagnetic metals. The different τ_{σ} and λ_{σ} mean that the scattering probability of the spin “up” conduction electrons differs with spin “down” conduction electrons. This phenomenon is named spin-dependent scattering, which is another mechanism. However, the spin-dependent scattering can be intrinsic and extrinsic, $N_{\sigma}(E_F)$ implied by and V_{σ} ,

respectively. As shown in Figure 1-2, $N_{\uparrow}(E_F) < N_{\downarrow}(E_F)$ resulting from the split of $3d$ band, gives $\rho_{\uparrow} < \rho_{\downarrow}$, indicating the asymmetric ratio of spin-dependent resistance $\alpha = \frac{\rho_{\downarrow}}{\rho_{\uparrow}} > 1$. In contrast, spin-dependent V_{σ} results $\alpha = \frac{\rho_{\downarrow}}{\rho_{\uparrow}} < 1$. For the ferromagnetic metals (i.e. Fe, Co, Ni) mixed with other metals, the concurrence of intrinsic and extrinsic spin-dependent scatterings can make the ratio α both larger than 1 and less than 1 [22].

According to the approximation under low temperature, Fert and Campbell propose the two-current model [22, 23] to explain the spin-dependent conduction in ferromagnetic metals. In this model, two separate electronic conduction channels for spin “up” ($\sigma = \uparrow$) and spin “down” ($\sigma = \downarrow$), which parallel each other, are established with the respective resistivities of $\rho_{\uparrow}$ and $\rho_{\downarrow}$. Therefore, the total effective resistivity is obtained as

$$\rho_t = \frac{\rho_{\uparrow}\rho_{\downarrow}}{\rho_{\uparrow} + \rho_{\downarrow}}. \quad (1-22)$$

For ferromagnetic metals under the Curie temperature, the spontaneous magnetization and spin-dependent scattering result in $\rho_{\uparrow} \neq \rho_{\downarrow}$, which is different with the normal metals ($\rho_{\uparrow} = \rho_{\downarrow}$). The total effective resistivity is always lower than that the resistivity of either channel due to the parallel relationship. Thus, the resistivity of ferromagnetic metals is dropped at Curie temperature.

Especially, in ferromagnetic multilayer thin films, the two-current model can indicate a giant magnetoresistance, which is discovered as GMR effect as a historic breakthrough [24, 25]. The GMR effect firstly shows the possibility to simultaneously regulate and control both charge and spin of electrons, differing with the traditional

Figure 1-3. The schematic of the two-current model in ferromagnetic multilayer thin films. The arrows in black, red, and blue colors represent the conduction channel, the magnetization direction in each layer, and the spin direction of the conduction electrons in each channel, respectively. The white five-pointed stars mean the occurring of scattering.

electronics and microelectronics where only the electron charge is used. The researches based on GMR effect then raise the development of emerging spintronics. Figure 1-3 shows the schematic of the two-current model in ferromagnetic multilayer thin films. The two black lines with arrows in Figure 1-3(a) or (b) represent the two electron channels. For current parallel to the surface of films, the direction of electron motion may be antiparallel to the surface. The small red arrows are the orientations of the magnetization in each layer. The small blue arrows at the end of the electron channels indicate the spin direction of the conduction electrons in each channel. The case of the spin direction of the conduction electrons parallel to the magnetization of the multilayer films, where less scattering occurs, is described by a straight line. The case of antiparallel, where more scattering occurs, is expressed by a broken line. In Figure 1-3(a), the magnetization of the multilayer films by magnetic field reaches saturation, which makes the same magnetization direction in each layer. The channel with low resistance shown by the black straight-line acts as a short circuit. Therefore, the Figure 1-3(a) indicates a low resistance state. In Figure 1-3(b), due to the interlayer

antiferromagnetic exchange coupling, the magnetization in adjacent layers is arranged spontaneously in antiparallel without external magnetic field, resulting in that the total magnetization of the multilayers is zero. Figure 1-3(a) shows a high resistance state, since both two channels have high resistance.

1.3 Magnetization dynamics

If a magnetic moment $\mathbf{m}$ is exposed to a magnetic field $\mathbf{H}$, a torque will be induced to attempt to align the moment in the same direction as the field vectors. In the classical physics, this torque acting on the magnetic moment is expressed by

$$\tau = \frac{d\mathbf{L}}{dt} = \mu_0 \mathbf{m} \times \mathbf{H}. \quad (1-23)$$

However, the magnetic moment $\mathbf{m}$ is the result of both spin and orbital angular momentums, according to the SOC. Then the angular momentum $\mathbf{L}$ should be replaced by the total angular momentum $\mathbf{J}$. The relationship of the magnetic moment and the total angular momentum is expressed by $\mu_l = \sqrt{l(l+1)}\mu_B$. Substituting it into equation (1-23), we can obtain

$$\frac{d\mathbf{m}}{dt} = -\gamma\mu_0 \mathbf{m} \times \mathbf{H}, \quad (1-24)$$

where γ is the electron gyromagnetic ratio. This equation describes the precession behavior of the magnetic moment, implying that both components of the magnetic moment perpendicular to the applied magnetic field and the moment change, with no change in the component along the direction of the field. Meanwhile, the action of the torque to align the magnetic moment with the applied magnetic field, means that both components of the magnetic moment perpendicular to the applied magnetic field and

the moment will be decreased to zero at the end. It must be achieved through a damping process, implying the addition of a damping term in equation (1-22).

In ferromagnetic materials, the precessional motion of the magnetization $\mathbf{M}$ is induced by an effective magnetic field $\mathbf{H}_{eff}$, which is determined by the external magnetic field, anisotropic field, exchange field, demagnetizing field, etc. In 1935, Landau and Lifshitz introduced an original equation (Landau-Lifshitz equation) to describe the precessional motion including damping [26-28],

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \gamma \frac{\alpha}{M_S} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{eff}), \quad (1-25)$$

where γ is the electron gyromagnetic ratio, α is the damping factor of a dimensionless constant, and M_S is the magnitude of the saturation magnetization. Later, Gilbert modified the Landau-Lifshitz equation in expression of [29, 30]

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha_G}{M_S} \mathbf{M} \times \frac{d\mathbf{M}}{dt}. \quad (1-26)$$

Here, the damping term becomes dependent on the time derivative of the magnetization and α_G is called Gilbert damping constant. The modified equation is then named Landau-Lifshitz-Gilbert (LLG) equation, which can better describe the real behavior of the magnetization in ferromagnetic materials. In LLG equation, the first term in the right side of this equation is called the driving torque, which causes the precession of the magnetization around the effective field. The second term in the right side of this equation is called damping torque, which forces the magnetization align to the effective field $\mathbf{H}_{eff}$. The terms of LLG equation are illustrated in Figure 1-4.

Figure 1-4. Illustration of different terms in the Landau–Lifshitz–Gilbert equation. The effective magnetic field $\mathbf{H}_{eff}$ (black) precesses the magnetization $\mathbf{M}$ (orange). The driving torque $-\gamma\mathbf{M} \times \mathbf{H}_{eff}$ in red color and the damping torque $\alpha_G\mathbf{M} \times d\mathbf{M}/dt$ in color are shown separately.

1.4 Spin-transfer torque

In the development of spintronics, spin-transfer torque (STT) effect predicted by Slonczewski [31] and Berger [32] in 1996 and experimentally confirmed soon after [33–35], is another historic breakthrough. The effect enables the change of the magnetization in nanomagnet induced directly by current, in addition to magnetic field. [31, 32, 36–38]

STT is produced by a spin polarized current (spin current) that is defined as a flow of electron spin. In spin current, the amounts of electrons with up- and down-oriented spins are not equal, which means that spin current carries a net spin angular momentum. When a spin current flow through an ferromagnet, a torque is generated via transferring spin angular momentum from spin current to the magnetization of the ferromagnet in case that the spin of the spin current is noncollinear with the magnetic moment of the ferromagnet. As shown in Figure 1-5, the basic physics of STT is illustrated. [38] In a

spin current going through a thin ferromagnetic layer, the outgoing electron spin is re-oriented due to the interaction between an incident electron spin and the magnetization of the ferromagnet, which indicates that the spin angular momentum of the electron is changed. According to the conservation of angular momentum, the change of the spin angular momentum is transferred to the ferromagnet. Consequently, a torque called STT is generated on the magnetization of the ferromagnet. The torque has two different terms, as directed in Figure 1-5. One is in the plane of the electron spins and called in-plane STT (or adiabatic torque or anti-damping torque). Another is perpendicular to the plane and regarded as an out-of-plane torque (or non-adiabatic torque or field-like torque).

Figure 1-5. Illustration of STT via the interaction between the spin current and the magnetization of ferromagnet. The bold vertical arrow in blue color represents the magnetization of the ferromagnet.

STT can be utilized to switch the magnetization of ferromagnet. [39-45] The magnitude of STT determines a threshold current for the magnetization switching, which is critical to its applications. The problem can be solved by studying the magnetization dynamics via LLG equation. As introduced in section 1.3.1, the

magnetization in ferromagnet will align with the effective field in the absence of external torques. The generation of STT will expand the LLG equation with the third term describing it. To describe the magnetization dynamics, the LLG equation with STT modification can be written as

Figure 1-6. Illustration of magnetization dynamics with STT.

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha_G}{M_s} \mathbf{M} \times \frac{d\mathbf{M}}{dt} + \tau_{STT}. \quad (1-27)$$

The two terms of STT can be included in different forms. The anti-damping torque can be written in the form of

$$\tau_{STT}^{\parallel} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{J}_s), \quad (1-28)$$

where $\mathbf{J}_s$ denotes the spin current. The field-like torque can be obtained by

$$\tau_{STT}^{\perp} \propto \beta \mathbf{M} \times \mathbf{J}_s, \quad (1-29)$$

where β gives the relative strength with respect to the anti-damping torque in equation (1-26).

The illustration of the magnetization dynamics with STT is shown in Figure 1-6. According to Figure 1-6, the anti-damping STT will counteract with the damping torque. For a threshold STT, which is larger than the damping torque, the magnetization can be switched to the opposite direction. The corresponding current generating the threshold STT is defined as the threshold current.

1.5 Spin-orbit effects and spin-orbit torque (SOT)

As introduced in section 1.1, the SOC describes the interaction of the spin and orbital angular momentums of an electron. The interaction can result in the spin polarization and the transport phenomenon of spin, which is called spin-orbit effect, e.g., Rashba effect [46-52] and spin Hall effect (SHE) [53-60]. In the structure of heavy metal/ferromagnetic metal (HM/ FM), the Rashba effect generates an effective electric field in the direction normal to the HM/ FM interface, leading to spin accumulation at the HM/ FM interface. The SHE gives rise to a spin current converted from the charge current and spin accumulation at the boundaries of heavy metals. In a HM/ FM bilayer, both effects will exert a torque on the magnetic moment in FM layer. The torque is named spin-orbit torque (SOT) to distinguish it from STT. [59]

1.5.1 Rashba effect

According to Eq. (1-18), the conducting electrons will experience a magnetic field in the rest frame of electrons in the flow of a current. As introduced in section 1.1, the intrinsic spin of an electron is 1/2, resulting in a magnetic moment $\boldsymbol{\mu}_s = -\mu_B \boldsymbol{\sigma}$. μ_B is the Bohr magneton and $\boldsymbol{\sigma}$ is the Pauli matrix of spin. Therefore, the interaction energy in

Eq. (1-19) can be approximated as $E_{SO} = -\boldsymbol{\mu}_s \cdot \mathbf{B} = \mu_B \boldsymbol{\sigma} \cdot \left(\frac{-1}{c} \mathbf{v} \times \mathbf{E}\right) \propto \boldsymbol{\sigma} \cdot (-\mathbf{p} \times \mathbf{z})$, where

$\mathbf{z}$ is the unit vector perpendicular to the interface and $\mathbf{p}$ is the momentum. [17, 61, 62]

Figure 1-7. Illustration of the Rashba effect at the HM/FM interface.

As illustrated in Figure 1-7, the interfacial Rashba effect originates from the SOC in systems with broken inversion symmetry, such as the HM/FM bilayer. [17] An internal electric field $\mathbf{E}$ is generated in the direction normal to the HM/FM interface. The conduction electrons near the interface will experience an effective magnetic field $\mathbf{B}$, which couples to and polarizes the magnetic moments of the conduction electrons. [63-69] The combination of the interfacial SOC and the induced effective electric field give rise to a Hamiltonian to describe the Rashba effect,

$$H_R = \alpha_R \boldsymbol{\sigma} \cdot (\mathbf{z} \times \mathbf{p}), \quad (1-30)$$

where α_R is the Rashba parameter. The conduction electrons will also have an exchange interaction with the local magnetization in the FM. As a result, the magnetization $\mathbf{M}$ in the FM can be aligned with the spin polarization $\boldsymbol{\sigma}$ of the conduction electrons. The Rashba Hamiltonian in Eq. (1-30) becomes to $H_R = \alpha_R \mathbf{M} \cdot (\mathbf{z} \times \mathbf{p})$. The effect of the Rashba Hamiltonian is equivalent to an effective magnetic field

$$\mu_0 \mathbf{H}_{\text{eff}} = \alpha_R (-\mathbf{z} \times \mathbf{p}) \propto \alpha_R (\mathbf{z} \times \mathbf{J}), \quad (1-31)$$

where $\mathbf{J}$ is current density of the applied in-plane current. The Rashba effect was initially observed in inversion asymmetric semiconductors [70] and two-dimensional electron gases (2DEGs) [71]. Then it is found and studied in the NM/ FM bilayers over the last decades. The review by Manchon *et al.* provides a detailed discussion of the Rashba effect and associated SOT. [72]

1.5.2 Spin Hall effect

The SHE arises from bulk SOC in the HM producing spin accumulations and a pure spin current by the conduction electrons passing through the HM, which is different with the Rashba effect. [73-79] In the ordinary Hall effect, the electric carriers with opposite signs move to opposite directions by the Lorentz force, producing the charges accumulations. Similarly, the electrons with opposite spins will be separated to accumulate at the two surfaces of the HM in SHE, which creates a perpendicular spin current when a charge current is injected into the HM. This is due to the asymmetric scattering of the conduction electrons with different spin orientations. However, no charge accumulation occurs in SHE, because the numbers of electrons moving to two surfaces are equal. [80-83]

The SHE can be attributed to both intrinsic and extrinsic mechanisms. The band structure gives rise to an intrinsic mechanism of the SHE. In the intrinsic SHE, the spin relaxation occurs in the scattering. The combination of the SOC and the inter band transitions induces a transverse velocity dependent on spin, such that the spin Hall conductivity σ_{xy} is independent of the momentum relaxation time τ . The intrinsic SHE can be expressed in terms of Berry curvature $\Omega_n^z(\mathbf{k})$:

$$\sigma_{xy} = \frac{e}{\hbar} \sum_{\mathbf{k}} \Omega^z(\mathbf{k}) = \frac{e}{\hbar} \sum_{\mathbf{k}} \sum_n f_{kn} \Omega_n^z(\mathbf{k}) \quad (1-32)$$

$$\Omega_n^z(\mathbf{k}) = \sum_{n \neq n'} \frac{2 \operatorname{Im} \left[\langle \mathbf{k}n | j_{zx} | \mathbf{k}n' \rangle \langle \mathbf{k}n' | v_y | \mathbf{k}n \rangle \right]}{\left(\varepsilon_{kn} - \varepsilon_{kn'} \right)^2} \quad (1-33)$$

where is v_y the charge velocity in the y direction, and f_{kn} is the Fermi distribution function for the n^{th} band at $\mathbf{k}$. [84-86] The Berry curvature is determined by the virtual inter-band transitions. SOC splits the degenerate bands in the band structure, which leads to non-zero Berry curvature. The bands on either side of the split gap contributes opposite nature of the Berry curvature. The intrinsic σ_{xy} is proportional to the spin-orbit polarization at the Fermi level. The contribution of the two opposite Berry curvature are not compensated in the band structure with the fermi level within the split gap. As a result, the intrinsic σ_{xy} is dominated.

Two extrinsic mechanisms, the skew and side-jump scatterings of electrons, are introduced by the high SOC of the impurities in HM. The spin relaxation occurs between and during the scattering for the former and latter, respectively. Moreover, in the skew scattering, different final directions of momentums for “up” and “down” spins are produced by the SOC. The spin Hall conductivity due to the skew scattering is $\sigma_{xy} \propto \tau$, where τ is the momentum relaxation time. The side-jump scattering is attributed to a spin-dependent difference in the acceleration and deceleration of conduction electrons during scattering. A spin-dependent displacement in the side-jump scattering leads that the spin Hall conductivity σ_{xy} is independent of the relaxation time τ . The contribution to the SHE from different mechanisms is still under debate, which needs further experimental quantification. [87-89]

Figure 1-8. Illustration of the bulk spin Hall effect in a HM.

The bulk SHE in a HM is illustrated in Figure 1-8. An injected in-plane charge ($\mathbf{J}_c$) current in the HM can be converted to a pure perpendicular spin current ($\mathbf{J}_s$) into the FM. [90-100] The polarization $\boldsymbol{\sigma}$ of the accumulated spins at the two surfaces of the HM is orthogonal to both the directions of the injected $\mathbf{J}_c$ and the generated $\mathbf{J}_s$. As a result, the generated spin current is obtained by the equation [101, 102]

$$\mathbf{J}_s = \frac{\hbar}{2e} \theta_{SH} (\mathbf{J}_c \times \boldsymbol{\sigma}). \quad (1-40)$$

Here, θ_{SH} is called spin Hall angle and quantified by the intrinsic property of the HM.

Figure 1-9. Illustration of the spin accumulation direction at the boundaries in Ta and Pt for the same charge current injection.

The magnitude of the spin Hall angle shows the efficiency of generating spin current for an injected charge current density. The sign of the spin Hall angle determines the orientation of the accumulated spins at the HM/FM interfaces. β -Ta has a spin Hall angle of around -0.15 and Pt has a spin Hall angle of around 0.06 . [89] The opposite signs of the spin Hall angles in Ta and Pt indicate opposite spin polarization at the surface of the HM for the same injected charge current, as shown in Figure 1-9.

As introduced, the SHE converts an unpolarized charge current to a pure spin current. A reverse process can generate a charge current from a pure spin current in the HM, which is named the inverse spin Hall effect (ISHE). [103, 104] The ISHE also originates from the same SOC effects as the SHE in the HM. The readers who are interesting in their mechanisms are encouraged to refer to reviews by Hoffman [89] and Sinova *et al.* [105]

1.5.3 SOT effective fields

As discussed in sections 1.4.1 and 1.4.2, both the Rashba effect and the SHE gives rise to the spin accumulation and SOT. [74, 106, 107] In the Rashba picture, the exchange interaction between the magnetization in FM and the itinerant spins is also necessary for the generation of SOT. In the case of only Rashba SOC without the exchange interaction, the Fermi surfaces are described by two spheres with different radius for “majority” and “minority” electrons, as introduced in section 1.2. Finite total spin density is obtained due to the opposite signs of the net spin density in each band, when the Fermi surfaces is displaced in the direction of the current by the electric field. As a sequence, no spin torque is exerted on the local magnetization in the absence of the exchange interaction. The Rashba SOC gives rise to the nonequilibrium spin density. The exchange interaction couples the spins with the local magnetization. They together

act as an effective magnetic field H_{FL} , generating a field-like SOT on the magnetization in the FM [108-111]

$$\boldsymbol{\tau}_{FL} = -H_{FL} \mathbf{M} \times \mathbf{p}. \quad (1-41)$$

In the picture of SHE, the charge current injected in the HM produces a spin current diffused into the FM layer. The electron spins moving into the FM can be reflected by the spin scattering in the FM layer, transferring the momentums and angular momentums to the magnetization in the FM. [112-114] As a result, the damping-like term of SOT is given by [110, 110, 115, 116]

$$\boldsymbol{\tau}_{DL} = -H_{DL} \mathbf{M} \times (\mathbf{m} \times \mathbf{p}). \quad (1-42)$$

Here, H_{DL} is the corresponding effective magnetic field.

The first experimental observation of SOT was carried out in dilute ferromagnetic semiconductor $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ films grown on the (001) surface of GaAs reported by Chernyshov et al. [117]. It provides the evidence for magnetization reversal in a dilute magnetic material by means of spin-orbit induced magnetic field contributed by the broken symmetry of the film structure. On the other hand, the first observation of a current-induced SOT in a ferromagnetic heterostructure consisting of a metallic thin Co layer sandwiched by Pt and AlO_x interfaces is reported by Miron et al. [46], which results from the broken symmetry of the interfaces. In the Pt/Co/ AlO_x heterostructures, Rashba and spin Hall effect induce the effective fields at the interface between the heavy metal and the ferromagnetic layer, to give rise to a torque on the local magnetization of thin Co layer resulting in the domain wall nucleation [46, 49]. Alternatively, a new case of an ultrathin Co layer sandwiched between two different heavy metals, Pt and Ta, which have spin Hall angles of opposite sign, is reported [53].

In this case, the SOTs from the top Co/Ta and bottom Pt/Co interfaces both contribute to enhance the total effective torque.

1.6 Motivation of SOT-based memory

Magnetic Random-Access Memory (MRAM), which relies on the controlled manipulating of the magnetization of magnetic materials, is an emerging memory technology promising advantages such as non-volatility, high density and scalability. As such, the research on the efficient and accurate switching of magnetization has been widely investigated with the aim of developing next generation magnetic memory devices. The conventional method of magnetization reversal in ferromagnetic materials is via external magnetic field or locally induced Oersted field by electrical current. In recent years, the move to manipulate the magnetization of ferromagnetic materials by using spin polarized electrical current opened a wider spectrum of opportunities to integrate magnetic functionalities into electronic circuits [32, 36, 118-120].

As introduced in section 1.4, the STT is induced by a spin-polarized current produced by spin filtering from a thin ferromagnetic film (the “fixed layer”), which is directed into another thin ferromagnetic film (the “free layer”) with different moment orientation, has attracted much attention as an efficient method to achieve the switching or reversal of the magnetization [36, 37, 119-121]. In this effect, partial angular momentum of the incident electrons is transferred to the free layer, inducing a torque interacting on the magnetic momentum of the free layer. It can be used to excite oscillations or even flip the direction of the magnetic moment of ferromagnetic materials in nanometer scale devices. STT-MRAM [122-135] has been proposed as a non-volatile and scalable magnetic memory device with the same read and write path. Memory devices comprising of STT-MRAM structures are already in the market for

specific applications [45]. However, STT-MRAM is restricted by the high write current and high energy consumption efficiency (10 times more energy employing per writing operation than Static Random-Access Memory) [36, 39, 59]. In STT-MRAM, the writing current and reading current flow in the same path, causing a disturbance. Due to the thermal wave, the magnetization can be reversed by a smaller current through the MTJ than the threshold current. Therefore, a high reading current may mislead a writing operation. Especially for nanoscale STT-MRAM, the difference between the writing and reading currents decreases. The read disturbance becomes more serious. Moreover, the resistance of MTJ is generally similar to transistor and the general value of TMR is 100% - 200%. As a result, the reading error can be easily caused by technological deviation of device. The disturbance is a critical problem to solve for designing STT-MRAM. [45, 59]

Recently, another novel current-induced spin torque mechanism, SOT discovered in ferromagnetic materials (FM) sandwiched between a heavy metal (HM) layer and an Oxide layer, has been proposed as a more efficient alternative to manipulate the magnetization [136-147]. As introduced in section 1.5, the concept of the spin-orbit interaction at the interface between ferromagnetic metal and non-magnetic metal layer is utilized for more efficient magnetization switching. The charge current passing through the HM layer induces effective fields mainly contributed by two known mechanisms: the SHE and the Rashba effect. Spin Hall effect arises due to spin current induced by the spin dependent electron scattering from the large SOC in heavy metals, such as Pt and Ta. The spin current exerts a torque on the local magnetization of the ferromagnetic layer. Rashba effect is a relativistic effect induced by strong SOC, leading to the effective magnetic field polarizing the spin of conduction electrons as well as the magnetization via s-d interaction. It is fundamentally different from the

processes of STT, relying on the presence of strong SOC in the intrinsic structure of a material.

Figure 1-10. Illustration of the cell of (a) STT-MARM and (b) SOT-MARM.

Compared to STT-MRAM, the recently proposed SOT-MRAM exhibits more advantages in the properties of memory devices, especially in the writing process [148-158]. In SOT-MRAM the reading and writing path are decoupled. The read stability of SOT-MRAM is significantly improved than STT-MRAM due to the orthogonal read and write path of SOT-MRAM. Furthermore, the write current of SOT-MRAM is much lower and the write access is much faster, because of the independently optimized write path. The STT-MARM and SOT-MARM are illustrated in Figure 1-10(a) and 1-10(b). Consequently, the solid understanding of SOT is critical in using this technology for the development of future magnetic memory devices. In this work, the SOT effective

fields and SOT-induced magnetization switching are studied in ferromagnetic multilayers with perpendicular magnetic anisotropy.

1.7 This thesis

Methods to manipulate the magnetization of ferromagnets by the electric current open a wide spectrum of opportunities to integrate magnetic functionalities into electronic circuits. One of them is SOT generated by spin-orbit interaction (SOI). Understanding the SOI behavior is critical for the design of SOT-based memory devices. Therefore, the SOT effective fields and the SOT switching are investigated in the thesis. In this thesis, systematic investigation of the physics governing the SOT-induced magnetization switching has been carried out by examining the SOT effective fields, *i.e.*, damping-like term and field-like term. AC harmonic Hall voltage measurement technique was applied to characterize the SOT effective fields in Pt/Co/Ta structure with PMA. It is found that the sign and magnitude of the damping-like term are dependent on the thickness of the inserted Pt layer at the Co/Ta interface, while that is negligible for the field-like term. In the Pt/Co/Pt/Co/Ta structure, the effective field strength is dependent on the lower Co layer thickness while no changes were observed with varying upper Co layer thickness. The asymmetric dependence of the SOT on the two Co layer thicknesses is attributed to the modulations of the saturation magnetization as a result of their different interface conditions. Additionally, by exploiting the intrinsic tilt of the magnetization in the Pt/[Co/Ni]₂/Co/Ta structure, it is shown that field-free SOT-induced magnetization switching is possible. Kerr imaging reveals that the field-free SOT switching process is completed via the nucleation of reverse domain and propagation of domain wall in the system.

Chapter 2 provides the details of films preparation and device fabrication process.

The characterization of the as-deposited magnetic films by the polar magneto-optic Kerr effect (MOKE) measurement and the Vibrating sample magnetometer (VSM) technique is described. The experimental techniques such as the anomalous Hall effect (AHE) and Planar Hall effect (PHE) measurements used in this work are briefly depicted. The SOT effective fields are derived using harmonic Hall voltage measurements.

Chapter 3 gives the characterization of SOT effective fields in Pt/Co/Pt (*t*)/Ta structure with perpendicular magnetic anisotropy (PMA) using AC harmonic Hall voltage measurement technique. Varying the thickness of the inserted Pt layer at the Co/Ta interface in the structure can change both the sign and magnitude of the damping-like term of SOT effective field. The field-like term is negligible as the Rashba effects at the Pt/Co and Co/Pt interfaces counteract each other. The ability to change the sign of the damping-like SOT allows control over the magnetic switching direction in SOT devices.

Chapter 4 presents the Co layer thickness dependence of SOT in Pt/Co/Pt/Co/Ta structures with PMA. It is found that the lower and upper Co layers give rise to different PMA behaviors and asymmetric Co layer thickness dependence of SOT. The harmonic Hall voltage measurements reveal that the effective fields tend to decrease with the lower Co layer thickness, whereas they remain at the same level as varying the upper Co layer thickness. The asymmetric Co layer thickness dependence of SOT is attributed to the different modulations of the saturation magnetization by the lower and upper Co layers, due to their different interface conditions. The result indicates a new scene of modifying SOT, which enhances the flexibility of SOT-based spintronic devices.

Chapter 5 describes the observation of field-free SOT-induced magnetization switching in micron sized Pt/[Co/Ni]₂/Co/Ta structure. Kerr-microscopy image reveals that the reversal process is completed via nucleation and propagation of a domain wall (DW) in the path of current within the cross structure, which is large enough for domain nucleation and extension mechanism. Due to the intrinsic tilt of the magnetization, the nucleated DW adopts a chiral DW configuration during the reversal process.

Chapter 6 gives a conclusion and future works.

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Chapter 2. Sample preparation and experimental techniques

In this chapter, the preparation techniques of the ultrathin magnetic films are presented. The characterization of the as-deposited magnetic films by the polar MOKE measurement and the VSM technique is then described. The process to pattern the films into Hall cross structures are indicated schematically. The experimental techniques such as the AHE and PHE measurements used in this work are briefly depicted. The SOT effective fields are derived using harmonic Hall voltage measurements.

2.1 Thin film deposition

In this thesis, the SOT effective fields and SOT-induced magnetization switching in perpendicularly magnetized multilayers are studied. The thin magnetic multilayer films in this work were deposited using DC magnetron sputtering deposition technique. [1,2] In the process of magnetron sputtering, the velocity of the moving electron is increased by the Lorentz force. The collision between the moving electrons and the atoms of working gas is thus enhanced, resulting in the increase of the sputtering rate. The DC magnetron sputtering can work at low pressure and sputtering voltage to lower the contamination of the films. On the other hand, it also enhances the energy of the incident atoms into the substrate surface, which improves the quality

of the films. Meanwhile, the energy of moving electrons decreases due to the collisions, such that the temperature of the substrate will not be too high.

Figure 2-1. Image of the AJA magnetron sputtering system.

All magnetic films were prepared at room temperature in an AJA magnetron sputtering system as shown in Figure 2-1. The base pressure of the chamber is lower than 10^{-8} Torr. After Argon (Ar) gas was released, the sputtering pressure was maintained as $\sim 10^{-3}$ Torr. [3, 4] All magnetic films were sputtered on Si/SiO₂ substrates. The thickness of each layer in the films can be controlled by deposition time. Capping layers, such as Ta and/or Ru, were used to prevent the samples from being oxidized.

2.2 Film characterization

The as-deposited films were firstly characterized by the MOKE to evaluate their magnetic anisotropy. Then the VSM technique was used to measure the saturation magnetization and anisotropy field of the deposited films.

2.2.1 Magneto-optic Kerr effect

In the MOKE, an incident linear polarized light interacts with the magnetization in a ferromagnetic thin film under external magnetic field. The reflected light will be elliptically polarized with a different main polarization axis. The reflected light contains the information of the component of the magnetization in the ferromagnetic film along longitudinal and polar directions. It is sensitive and non-invasive to measure the magnetic hysteresis of an ultrathin magnetic film by using the MOKE technique. [5-8]

Figure 2-2 shows the schematic of the polar MOKE setup. A diode laser was used as the light source. The incident beam was focused on the surface of magnetic films after going through a polarizer, an optical chopper, a spectroscopy, and a magnet core. The chopper chopped the beam in frequency of 157 Hz, which was used as the input reference signal of a lock-in amplifier. The polarization of the reflected beam became different due to the interaction between the incident polarized beam and the magnetization of magnetic films. The electromagnet was used to apply a magnetic field along the normal of the films to control the interaction. The reflected beam is analyzed and detected by a lock-in amplifier. However, the MOKE technique cannot give the results of the saturation magnetization and anisotropy field of the deposited films. The reflected beam was reoriented by the spectroscopy after going through the magnet core and went into a detector after analyzed by the second polarizer. The

detected signal was output by the lock-in amplifier. The magnetic field was swept to obtain the magnetic hysteresis loops of magnetic films.

For instance, the magnetization hysteresis loop of Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Ta (3 nm) thin film measured by polar MOKE technique is shown in Figure 2-3. The square loop evidences the PMA of the film. The coercivity is obtained to be ~30 Oe.

Figure 2-2. Schematic of the polar MOKE setup.

Figure 2-3. Magnetization hysteresis loop of Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Ta (3 nm) thin film measured by polar MOKE technique.

2.2.2 Vibrating sample magnetometer

VSM is generally used to obtain the magnetic hysteresis behaviors of materials. Parameters such as coercivity H_C , saturation magnetization M_S , and anisotropy field H_K , can be obtained. The VSM utilizes the principle of electromagnetic induction and it is used to measure small sample [9, 10], with a typical size of $4 \text{ mm} \times 4 \text{ mm}$. The small sample can be seen as a magnetic dipole, after it is magnetized in a uniform magnetic field. During the measurements, the small sample is vibrated harmonically at a frequency ω , forming a vibrating magnetic dipole. The alternating magnetic field produced by the vibrating magnetic dipole changes the magnetic flux through the detection coils. A voltage ε proportional to the total magnetic moments M of the

sample is then induced as

$$\varepsilon = KM. \quad (2-1)$$

Here, K is a constant and can be determined by a standard sample. Therefore, the total magnetic moments can be measured by detecting the induced voltage using a lock-in amplifier, after calibration using a standard sample. The saturation magnetization is obtained by $M_s = M/V$, where V is the volume of the magnetic material in the sample.

The Lakeshore model 8600 Vibrating Sample Magnetometer as shown in Figure 2-4 was used in this work.

Figure 2-4. Image of the Lakeshore model 8600 Vibrating Sample Magnetometer.

The Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Ta (3 nm) thin film was characterized by VSM as an example. The measured out-of-plane and in-plane magnetic hysteresis loops are shown in Figures 2-5(a) and 2-5(b). The film exhibits PMA with a coercivity of ~ 30

Oe as evidenced by the square out-of-plane hysteresis loop with sharp switching in Figure 2-5(a). The values of coercivity measured by MOKE and VSM are the same. The saturation magnetization M_s and anisotropy field H_k were measured to be ~ 539 emu/cm³ and ~ 3.7 kOe, respectively.

Figure 2-5. Normalized magnetic hysteresis loops measured by VSM when out-of-plane (a) and in-plane (b) magnetic fields were applied.

2.3 Device fabrication

The deposited films were patterned into Hall cross structures using a combination of electron beam lithography (EBL) and Ar⁺ ion milling techniques. [1-4] The used Raith EBL system and AJA Ar⁺ ion milling system are shown in Figure 2-6 and Figure 2-7.

For the experiments, the sample fabrication process can mainly be divided into two sections, as shown in Figure 2-8(a) and 2-8(b), respectively. The first section describes the process of fabricating the Hall bar structure. We start with a Si/SiO₂(300 nm) wafer of 1cm $\times$ 1cm which is cleaned by acetone for 15 minutes and IPA for 15 minutes in ultrasonic irrigation. Then we deposit the sample films on the wafer by AJA magnetron sputtering system. A thin negative photoresist (MAN 2403) film is spin coated upon the

Figure 2-6. Raith EBL system.

Figure 2-7. AJA Ar⁺ ion milling system.

sample film. After this, the whole wafer with photoresist and sample films is patterned via an EBL system. Due to the properties of negative photoresist, the area exposed by

the electron beam hardens. After we wash the treated wafer in MAD for 45 seconds for 2 times and then in DI-water for 2 minutes, only the area exposed by e-beam can be left for the photoresist film. Then the Ar⁺ ion milling is done to eliminate the sample film not protected by photoresist film to produce cross Hall bar structure as designed. At last, we remove it using in MR-remover in ultrasonic irrigation for about 10 hours.

Figure 2-8. Schematic illustration of sample fabrication process. (a) The process of the Hall cross structure fabrication. (b) The process of the contact pads fabrication.

Then the second section is the process of fabricating the contact structure. This section is the continuous process of the first section. We start with the wafer already patterned in the first section, where the Hall cross bar structure of the sample has been fabricated. We firstly spin coat the positive photoresist (PMMA) film on the sample. The similar e-beam exposure operation is made with the same EBL system. The exposure of this section was done according to the coordinate established in the first exposure operation accurately. After exposure, we do the development by washing the sample in MIBK for 30 seconds and in IPA for 30 seconds to clean the exposed parts. Then we deposit the electrode film using a six targets magnetron sputter system. The electrode film consists of Au, Cu and Ta from top to bottom. At last, we wash the sample by acetone for 30 seconds and IPA for 30 seconds in ultrasonic irrigation to lift-off the unexposed area.

2.4 Electrical measurements

As introduced in section 2.3, the deposited magnetic films were patterned into Hall cross structures. Figure 2-9 shows scanning electron microscopy (SEM) image of the fabricated device with illustrated electrical measurement configuration. [1,2] Hall bar structure is of $80\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ with a uniform width of $5\text{ }\mu\text{m}$. Contact pads of Ta (5 nm)/Cu (120nm)/Au (5nm) were deposited following a second EBL step to connect the Hall cross structure with electrical instruments. A DC or AC current was applied through the wire along x-direction and the voltage across the Hall bar along y-direction was detected for all performed measurements at room temperature.

Figure 2-9. Electrical measurement configuration superimposed on the SEM image of fabricated device.

2.4.1 Anomalous Hall effect measurement

The transport measurements are mostly dependent on the AHE in the FM. The AHE leads to an additional larger Hall voltage, which is proportional to the out-of-plane magnetization in the FM. It is generally used to characterize the magnetization in the FM devices. The Hall resistance contributed AHE can be expressed by

$$R_H = \frac{1}{2} R_{AHE} \cos \theta, \quad (2-2)$$

where R_H is the Hall resistance of the device, θ is the polar angle of the magnetization vector, and R_{AHE} is called the AHE resistance.

To measure the AHE resistance R_{AHE} , a small current is applied through the channel along the x -axis using a Keithley 2400 current source meter, and the voltage across the Hall bar along the y -axis is detected by a Keithley 2000 voltage meter or a lock-in amplifier. The out-of-plane loop of the Hall resistance R_H can be obtained by sweeping the out-of-plane magnetic fields during the measurements. Figure 2-10 shows the measured result of the AHE measurement in a Pt/Co/ Pt/Co/Ta device. The square AHE

loop evidences the PMA of the device. The AHE resistance R_{AHE} is obtained to be about 0.9Ω .

Figure 2-10. The loop of R_H as a function of applied out-of-plane magnetic field.

2.4.2 Planar Hall effect measurement

The planar Hall effect contributes the Hall resistance with respect to both the polar (θ) and azimuthal (φ) angles of the magnetization vector. The Hall resistance due to PHE can be written as

$$R_H = \frac{1}{2} R_{PHE} \sin^2 \theta \sin 2\varphi. \quad (2-3)$$

R_{PHE} is the planar Hall resistance. To measure the planar Hall resistance, a constant external magnetic field was applied in the in-plane direction ($\theta_H = \pi/2$). The applied external field should be strong enough to tilt the magnetization in the in-plane direction. The magnetization tilt angle (θ) was assumed to be independent of the azimuthal angle

of the external magnetic field. The sample stage was rotated between 0 to 2π , which means that the azimuthal angle of external magnetic field also varies between 0 to 2π , while the Hall resistance was measured. The Hall resistance R_H becomes a sinusoidal function of the azimuthal angle of external magnetic field. As shown in Figure 2-11 are the experimental result of a Pt/Co/Ta device. The planar Hall resistance R_{PHE} is quantified to be $R_{PHE} \approx 0.25 \Omega$, as the amplitude of the expected sinusoidal fitting in Figure 2-11.

Figure 2-11. The Hall resistance as a function of the azimuthal angle of the fixed in-plane magnetic field.

2.4.3 Harmonic Hall voltage measurement

Recently, an adiabatic (low frequency) harmonic Hall voltage measurement technique, has been developed (originally by Pi *et al.*) to measure the magnitude and

direction of the effective magnetic field [11] that acts on the local magnetic moments in ferromagnetic heterostructures, as an efficient method to evaluate SOT. The harmonic Hall voltage measurement has previously shown that the effective field induced by SOT strongly depends on the thickness of heavy metal and ferromagnetic layer [12]. The strong angle (the angle between the magnetization and the current flow orientation) dependence of the effective field has also been exhibited in the reference [13]. Additionally, the effect that the spin current generated in a Pt layer can flow through a Cu spacer and exert torques on the magnetization of the magnetic layer, has been detected and reported by a similar technique [14]. All these experimental results indicate that the adiabatic harmonic Hall voltage measurement is a capable tool to measure the effective fields in ultrathin ferromagnetic heterostructures produced by SOT.

Figure 2-12. Schematic depiction of fabricated Hall cross structure and definition of the coordinate system used. θ (θ_H) and ϕ (ϕ_H) are the polar and azimuthal angles of the magnetization M (external magnetic field H) vector, respectively.

For the purpose of understanding the magnitude and direction of the effective fields induced by SOT, the illustration of harmonic Hall voltage measurement for a ferromagnetic heterostructure system with PMA is shown in Figure 2-12. The magnetic energy density of the system can be expressed as [2, 15]

$$E_{total} = -K_{eff} \cos^2 \theta - K_{in} \sin^2 \theta \sin^2 \varphi - \mathbf{M}_s \cdot \mathbf{H}, \quad (2-4)$$

Where the effective perpendicular anisotropy energy is $K_{eff} = K_u - \frac{1}{2}(N_z - N_x)\mu_0 M_s^2$. K_u is the uniaxial perpendicular magnetic anisotropy energy and defined a positive value for out of plane magnetic easy axis (z-axis). $\mathbf{M}_s$ is the saturation magnetization, and the in-plane anisotropy energy $K_{in} = \frac{1}{2}(N_x - N_y)\mu_0 M_s^2$ is from the shape anisotropy of the nanowire. K_{eff} and K_{in} are expressed using the demagnetization coefficients N_i ($\sum_{i=x,y,z} N_i = 4\pi$). In this system, the demagnetization factors along basic directions satisfy $N_z \gg N_y > N_x$ due to the geometry of the wire. The in-plane easy axis in our system is along the x-axis (the wire direction). Hence, we neglect N_x and N_y , and set $N_z = 4\pi$ for the convenience of computation. Then energy can be obtained as

$$E_{total} = (-K_u + 2\pi\mu_0 M_s^2) \cos^2 \theta - \mathbf{M}_s \cdot \mathbf{H}. \quad (2-5)$$

When an electric current is applied to the sample device, the current induced effective fields $\Delta H_{x,y,z}$, including the Oersted field, can induce torques to modify the magnetization angle from its equilibrium position (θ_0, φ_0). The equilibrium magnetization direction (θ_0, φ_0) is calculated by the following two equations:

$$\frac{\partial E_{total}}{\partial \theta} = 0 \quad (2-6)$$

and

$$\frac{\partial E_{total}}{\partial \varphi} = 0. \quad (2-7)$$

The Hall resistance typically is obtained from the two contributions, the AHE and the PHE [1]. R_{AHE} and R_{PHE} are defined as the variation of the Hall resistance due to the AHE and PHE, respectively. The Hall resistance R_{xy} is expressed as

$$R_{xy} = \frac{1}{2} R_{AHE} \cos \theta + \frac{1}{2} R_{PHE} \sin^2 \theta \sin 2\varphi. \quad (2-8)$$

The Hall voltage V_{xy} is a product of the Hall resistance R_{xy} and the applied current I_x , V_{xy} is expressed as

$$V_{xy} = R_{xy} I_x. \quad (2-9)$$

The AC current $I_x = I_0 \sin \omega t$, related to the oscillating effective field is applied. The polar and azimuthal angles will oscillate as $\sin \omega t$. The polar and azimuthal angles are expressed as $\theta = \theta_0 + \Delta \theta \sin \omega t$ and $\varphi = \varphi_0 + \Delta \varphi \sin \omega t$. $\Delta \theta$ and $\Delta \varphi$ are the modulation amplitudes of the magnetization angle from its equilibrium position (θ_0 , φ_0).

The Hall voltage V_{xy} can be expressed in harmonic form as

$$V_{xy} = V_0 + V_\omega \sin \omega t + V_{2\omega} \sin 2\omega t + \dots, \quad (2-10)$$

where V_ω and $V_{2\omega}$ are the first and second harmonic voltage, respectively.

For our system, the initial magnetization $\mathbf{M}_s$ is towards perpendicular to the film plane due to a high K_{eff} . The equilibrium magnetization position deviates very small from the z -axis. Therefore, $\theta_0 = \theta'_0$ ($\theta'_0 \ll 1$) for initial up magnetization state ($\mathbf{M}_s$ along $+z$ direction) and $\theta_0 = \pi - \theta'_0$ for initial down magnetization state ($\mathbf{M}_s$ along $-z$ direction). Keeping the linear terms of θ'_0 , eqs. (2-5) and (2-6) give

$$\theta_0' = \frac{H \sin \theta_H}{H_K \pm H \cos \theta_H}, \varphi_0 = \varphi_H. \quad (2-11)$$

Here, H_K is defined by $H_K = \frac{K_u - 2\pi\mu_0 M_s^2}{M_s}$. The $\pm$ sign corresponds to the case for up magnetization and down magnetization, respectively.

Combining eqs. (2-5) - (2-11), we can obtain

$$V_\omega \approx \pm \frac{1}{2} I_0 R_{AHE} \left[1 - \frac{1}{2} \left(\frac{H \sin \theta_H}{H_K \pm H \cos \theta_H} \right)^2 \right], \quad (2-12)$$

and

$$V_{2\omega} \approx \pm \frac{1}{4} I_0 R_{AHE} (\Delta H_x \cos \varphi_H + \Delta H_y \sin \varphi_H) \times \frac{H \sin \theta_H}{(H_K \pm H \cos \theta_H)^2}. \quad (2-13)$$

Here, we neglect the contribution of PHE.

We consider the case of an external in-plane magnetic field, $\theta_H = \frac{\pi}{2}$. With a longitudinal field H_x along the x direction ($\varphi_H = 0$) is applied, we can get

$$V_\omega = \pm \frac{1}{2} I_0 R_{AHE} \left(1 - \frac{H_x^2}{2H_K^2} \right), \quad (2-14)$$

and

$$V_{2\omega} = \pm \frac{1}{4} I_0 R_{AHE} \Delta H_x \frac{H_x}{H_K^2}. \quad (2-15)$$

When a transverse field H_y along the y direction ($\varphi_H = \frac{\pi}{2}$) is applied, we drive

$$V_\omega = \pm \frac{1}{2} I_0 R_{AHE} \left(1 - \frac{H_y^2}{2H_K^2} \right), \quad (2-16)$$

and

$$V_{2\omega} = \pm \frac{1}{4} I_0 R_{AHE} \Delta H_y \frac{H_y}{H_K^2}. \quad (2-17)$$

The $\pm$ signs correspond to the case for up and down magnetization states, respectively.

Finally, the SOT effective fields can be obtained as follows:

$$\Delta H_x = -2 \frac{\partial V_{2\omega}}{\partial H_x} \bigg/ \frac{\partial^2 V_{\omega}}{\partial H_x^2} = H_L, \quad (2-18)$$

and

$$\Delta H_y = -2 \frac{\partial V_{2\omega}}{\partial H_y} \bigg/ \frac{\partial^2 V_{\omega}}{\partial H_y^2} = H_T, \quad (2-19)$$

Here, the contribution of PHE and Oersted field is neglected [2]. The respective slope and curvature of $V_{2\omega}$ and V_{ω} as a function of the external field are evaluated from the equation.

Take the PHE into consideration, the effective fields, damping-like term H_{DL} and field-like term H_{FL} terms are given by [1, 15]

$$H_{DL} = \frac{H_L \pm 2\xi H_T}{1 - 4\xi^2}, \quad (2-20)$$

and

$$H_{FL} = \frac{H_T \pm 2\xi H_L}{1 - 4\xi^2}. \quad (2-21)$$

Here, ξ is the ratio of R_{PHE} and R_{AHE} , defined as $\xi = \frac{R_{AHE}}{R_{PHE}}$.

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Chapter 3. Characterization of SOT effective fields in Pt/Co/ Pt/Ta structures

In this chapter, AC harmonic Hall voltage measurement technique was applied to characterize the SOT effective fields in Pt/Co/Ta structure with PMA. It is found that the sign and magnitude of the damping-like term are dependent on the thickness of the inserted Pt layer at the Co/Ta interface, while that is negligible for the field-like term. The ability to change the sign of the damping-like SOT allows control over the magnetic switching direction in SOT devices. Additionally, we have observed an unusual SOT-induced magnetization switching in the Pt/Co/Ta structure, where the switching only responded to applied positive current. The preliminary investigation of this observation is presented in Appendix.

3.1 Motivation

The manipulation of magnetization using local electric currents has been widely studied because of its prospects in non-volatile magnetic memory and logic devices [1-4]. For instance, the STT technique has been used to excite oscillations or even switch

the magnetic moments of magnetic materials in magnetic nanodevices [5-7]. Recently, current-induced SOT in ultrathin heavy metal (HM)/ferromagnet (FM) heterostructure has gained prominence as a more efficient alternative for magnetization switching [8-11], as well as faster domain wall propagation [12-15]. SOT is proposed to arise mainly from two spin-orbit effects: the spin Hall effect (SHE) [9, 10] and the Rashba effect [8, 16]. Enhanced SOT with both damping-like H_L and field-like H_T terms has been observed in Pt/Co/Ta structure [17]. The enhancement of the damping-like term is attributed to the sum of the large SHE from both Pt and Ta layers, as they have opposite spin Hall angles. The modulated Rashba effect at the Pt/Co and Co/Ta interfaces can enhance the effective spin accumulation, resulting in an enhanced field-like SOT.

In most works, the SOT-driven magnetization switching has been investigated via the modulation of the damping-like SOT and the Dzyaloshinskii-Moriya interaction (DMI) effect [14, 18, 19]. As the field-like torque does not add on to the efficiency of SOT switching, the Rashba effect should be kept to a minimum. However, the SHE and Rashba effect generally both exist and contribute to SOT in ferromagnetic heterostructures. The portion of the contributions from the SHE and Rashba effect is always unclear. By introducing the Pt insertion in Pt/Co/Ta structure, the effect of Rashba becomes negligible. The SHE only contributed SOT behaviors can be investigated. Moreover, the ability to simultaneously and continuously tune the magnitude and direction of SOT is still lacking. By introducing the Pt insertion in Pt/Co/Ta structure, the SOT can be continuously tuned from positive to negative by varying the thickness of the inserting Pt layer. It provides a way to tune SOT without affecting DMI, which will be helpful for designing SOT-based memory and logic devices.

In this chapter, we studied the effect of inserting a Pt layer at the Co/Ta interface on SOT in Pt/Co/Ta. Using the AC harmonic Hall voltage measurement technique, large SOT effective fields in perpendicularly magnetized Pt/Co/Ta structure were firstly obtained. The inserted Pt layer at the Co/Ta interface results in negligibly small field-like SOT, due to counteracting Rashba effects at the interfaces of Pt/Co and Co/Pt. The damping-like term was found to be tuned by the thickness of the Pt insertion layer, which changes both sign and magnitude of the SOT effective fields. The contribution from the Ta layer diminishes with increasing Pt insertion layer thickness. The sign reversal of the damping-like SOT effective field also leads to opposite magnetic switching direction.

3.2 SOT effective fields in Pt/Co/Ta structure

Control sample comprising of sub./Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Ta (3 nm) stack was prepared using the DC magnetron sputtering deposition technique. The stack was patterned into Hall cross structures using EBL and Ar⁺ ion milling techniques. The harmonic Hall voltage measurements were performed on the fabricated Pt/Co/Ta structure using an AC current density J that varies from 1×10^{10} A/m² to 1×10^{11} A/m². The measured results are shown in Figure 3-1. The first harmonic signals in Figure 3-1(a) and Figure 3-1(b) indicate that domain walls are induced during the measurements. Some values of the second harmonic signals are not correct because they are larger than the auto range of the lock-in amplifier, which is evidenced by the horizontal lines in Figure 3-1(c) and Figure 3-1(d).

Figure 3-1. The measured first and second harmonic signals by AC harmonic Hall voltage measurements.

To make the uniform magnetic moments during the measurements, an additional out-of-plane magnetic field of ~ 80 Oe aligning with the magnetization is applied. The measured results with H_x or H_y quasi-statically swept between ± 700 Oe are shown in Figure 3-2. Figures 3-2(a) and 3-2(c) show the typical first and second harmonic Hall voltage signals versus H_x at AC current density $J = 5 \times 10^{10}$ A/m 2 for both up ($M_z > 0$) and down ($M_z < 0$) magnetized states. Figures 3-2(b) and 3-2(d) show the corresponding data for H_y . V_{ω} shows the same parabolic variation with H_x and H_y , and for up and down magnetized states, the variation tendency is opposite in the range. $V_{2\omega}$ varies linearly with both H_x and H_y . While the slope sign for H_x is dependent on the magnetization states, it is independent on the magnetization states for H_y , as expected for H_L and H_T , respectively.

Figure 3-2. The measured first and second harmonic signals by AC harmonic Hall voltage measurements with the assistance of a small out-of-plane magnetic field.

Figure 3-3. (a) In-plane and out-of-plane (inset) magnetic field dependence of the Hall resistance R_H . (b) The Hall resistance as a function of the azimuthal angle of the fixed in-plane magnetic field.

The R_H measurement was also carried out by passing a 100 μA DC current in the patterned structure with sweeping in-plane and out-of-plane magnetic fields, as shown in Figures 3-3(a). The obtained square out-of-plane AHE loop, as shown in the inset of Figures 3-3(a), indicates that the device has a strong PMA. The measured AHE resistance was $R_{\text{AHE}} \approx 1.02 \, \Omega$. The effective out-of-plane and in-plane magnetic anisotropy fields were calculated by fitting to the x -axis and y -axis magnetic field dependence of R_H and found to be around 8.3 kOe and 500 Oe, respectively. To measure the planar Hall resistance, a constant external magnetic field of ~ 8 kOe was applied to the sample in the in-plane direction ($\theta_H = \pi/2$). The external field is comparable to the magnetic anisotropy fields and is therefore large enough to tilt the magnetization in the in-plane direction ($\theta = \pi/2$). The magnetization tilt angle (θ) was assumed to be independent of the azimuthal angle of the external magnetic field. The sample stage was rotated between 0 to 2π , which means that the azimuthal angle of external magnetic field also varies between 0 to 2π , while the Hall resistance was measured. The Hall resistance R_H becomes a sinusoidal function of the azimuthal angle of external magnetic field, as shown in Figures 3-3(b). R_{PHE} was quantified to be $R_{\text{PHE}} \approx 0.25 \, \Omega$, as the amplitude of the expected sinusoidal fitting. The ratio of R_{PHE} and R_{AHE} was calculated to be $\xi = R_{\text{PHE}}/R_{\text{AHE}} \approx 0.25$.

Combining Eqs. (2-18)-(2-21), the effective fields of Pt/Co/Ta sample were computed and plotted as a function of AC current density J in Figures 3-4(a) and 3-4(b) for up and down magnetized states, including both $H_{\text{DL}(\text{FL})}$ and $H_{\text{L}(\text{T})}$. Both $H_{\text{DL}(\text{FL})}$ and $H_{\text{L}(\text{T})}$ increase linearly with J . H_{DL} and H_{L} have opposite signs for up and down magnetized states, while the sign is the same for H_{FL} and H_{T} . The effective fields are enhanced by ~ 1.6 times for the damping-like term and ~ 4 times for the field-like term after PHE correction, indicating that the PHE has a stronger influence on field-like SOT.

SOT efficiency is defined as the effective field per unit AC current density $dH_{DL(FL)}/dJ$, characterized by the slope of the linear fitting curves of the $H_{DL(FL)}$ versus J . Irrespective of the initial magnetization states, $\left(\left|dH_{DL(FL)}^+/dJ\right|+\left|dH_{DL(FL)}^-/dJ\right|\right)/2$ is taken from Figures 3-4(a) and 3-4(b) to evaluate the effective fields, where $+$ ($-$) sign represents up (down) magnetized state. The SOT efficiencies for the damping-like term and field-like term are evaluated as 160 Oe per 10^{11} A/m² and 108 Oe per 10^{11} A/m², respectively. The damping-like term originates from the large SHE from both Pt and Ta layers, as they have opposite spin Hall angles. The field-like term is attributed to the Rashba effects at the Pt/Co interface and Co/Ta interface.

Figures 3-4. The obtained effective fields of Pt/Co/Ta structure as a function of AC current density for (a) damping-like term and (b) field-like term with the assistance of an out-of-plane field of ~ 80 Oe. H_{DL} (H_L) and H_{FL} (H_T) are damping-like term and field-like term after (before) PHE correction, respectively.

(down) magnetized state. The SOT efficiencies for the damping-like term and field-like term are evaluated as 160 Oe per 10^{11} A/m² and 108 Oe per 10^{11} A/m², respectively. The damping-like term originates from the large SHE from both Pt and Ta layers, as they have opposite spin Hall angles. The field-like term is attributed to the Rashba effects at the Pt/Co interface and Co/Ta interface.

To show the effect of the applied out-of-plane field on the SOT, the measurements were repeated by applying another out-of-plane field of ~ 160 Oe. The measured effective fields are shown in Figures 3-5. The results are the same as the case of applied out-of-plane field of ~ 80 Oe. Therefore, the applied small out-of-plane magnetic field under 160 Oe has no effect on SOT.

Figures 3-5. The obtained effective fields of Pt/Co/Ta structure as a function of AC current density for (a) damping-like term and (b) field-like term with the assistance of an out-of-plane field of ~ 160 Oe. H_{DL} (H_L) and H_{FL} (H_T) are damping-like term and field-like term after (before) PHE correction, respectively.

3.3 Tuning SOT effective fields by Pt layer insertion

Using similar experimental procedure, the set of samples with Pt inserted between Co/Ta interface were investigated. The thin film stacks comprising of sub./Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Pt (t)/Ta (3 nm) were deposited by DC magnetron sputtering system, where t varies from 0.9 nm to 4 nm. The same fabrication process and electrical measurements were performed on the new set of samples. Figure 3-6 shows the harmonic Hall voltage signals for the $t = 0.9$ nm sample: first harmonic Hall voltage signals with 3-6(a) longitudinal magnetic field H_x and 3-6(b) transverse external magnetic field H_y for up and down magnetization; second harmonic Hall voltage signals with 3-6(c) longitudinal magnetic field H_x and 3-6(d) transverse magnetic field H_y for up and down magnetization. The significant difference is observed from the second

harmonic Hall voltage signals with H_x and H_y . The clear signal in Figure 3-6(c) indicates the effect of SHE. However, there is no obvious change in the second harmonic Hall signal when sweeping the magnetic field along the y -axis under the same current value, as shown in Figure 3-6(d). The zero slope indicates that the Rashba effect is cancelled out, which is attributed to the counteractive effects at the Pt/Co interface and Co/Pt interface [24]. As a result, the field-like effective field is negligible. Similar results were obtained for varying thickness of Pt insertion layer up to 4 nm.

Figure 3-6. Harmonic Hall voltage signals of $t = 0.9$ nm sample: first harmonic Hall voltage signals with (a) longitudinal magnetic field H_x and (b) transverse magnetic field H_y for up and down magnetization; Second harmonic Hall voltage signals with (c) longitudinal magnetic field H_x and (d) transverse magnetic field H_y for up and down magnetization.

The damping-like SOT efficiencies of the set of samples were calculated and plotted as a function of the inserted Pt layer thickness t in Figure 3-7, including the

result for $t = 0$ nm sample. The damping-like SOT has the largest value at $t = 0$ nm, and it decreases once the Pt layer is inserted. As the Pt insertion layer thickness t increases, the damping-like SOT gradually decreases to zero up to approximately 2 nm, and then subsequently increases towards opposite sign. Finally, the damping-like SOT saturates for $t \geq 3$ nm. When the Pt insertion layer thickness is thinner than 0.9 nm, both the Pt and Ta layers contribute to the damping-like term. At the thicknesses above 0.9 nm, the contribution from Ta layer becomes insignificant. In contrast with Pt/Co/Ta structure, opposite spin currents from the inserted Pt and bottom Pt layers flow toward the Co layer, resulting in the reduction of the overall torque. For $t = 3$ nm, the spin current from the inserted Pt layer is the same as that from bottom Pt layer, leading to a cancelled bulk SHE. Therefore, the symmetric Pt (3 nm)/ Co (0.9 nm)/ Pt (3 nm) structure should have no SOT. While our result is not the case. Bandiera et. al. reported that the inter-diffusion at the top Co/Pt interface contributes a lower perpendicular magnetic anisotropy than the bottom Pt/Co interface [25]. The result implies that more Pt atoms are mixed with Co atoms at the top Co/Pt interface than the bottom Co/Pt interface. The side-jump scattering occurs when the spin dependent acceleration and deceleration in the Pt layers are different during the scattering of electrons, resulting in an effective transverse displacement of the electron. It contributes a spin Hall conductivity and a spin Hall angle that are proportional to the impurity concentration [26]. Therefore, the SHE from the side-jump scattering can be asymmetric at the top Co/Pt and the bottom Pt/Co interfaces [25, 26]. The top Co/Pt interface can provide higher interfacial SHE than the bottom Pt/Co interface, due to the greater impurity concentration at the top Co/Pt interface. The SHE differences determines a net interfacial SHE, which contributes the damping-like SOT from the top Co/Pt interface. The interfacial SHE contribution can be transferred to that from an extra thin Pt inserting layer with thickness of Δt , which

means that the effective thickness of the Pt inserting layer is $t+\Delta t$. As a result, the zero damping-like SOT is obtained at $t \approx 2.2$ nm, which is thinner than the bottom Pt layer of 3 nm. Δt is estimated to be $\Delta t \approx 0.8$ nm. The result shows that the damping-like SOT can be continuously tuned by the inserted Pt layer, including both the sign and magnitude of the SOT effective fields.

Figure 3-7. The damping-like SOT efficiency as a function of inserted Pt thickness for up and down magnetized states.

3.4 Dependence of SOT switching direction on the sign of damping-like SOT

To study the effect of the sign reversal behavior on SOT-driven magnetization switching in the presence of an in-plane magnetic field to break the symmetry, an in-plane field of 2 kOe was applied and a quasi-static in-plane current was swept across

the wire. By measuring the dependence of Hall resistance on the current, a hysteretic magnetic switching between up and down magnetization states for samples $t = 0, 0.9, 3$ nm, was observed in Figure 3-8 with the in-plane bias field along 3-8(a) $+x$ and 3-8(b) $-x$ directions. The positive and negative in-plane magnetic fields result in opposite magnetization switching directions, as shown in Figure 3-8(a) and 3-8(b), respectively. With the same in-plane magnetic field, the $t = 3$ nm sample has an opposite switching behavior, which is due to the sign reversal of the damping-like SOT. The result shows that the magnetic switching direction can be controlled by both the direction of external in-plane magnetic field and the sign of damping-like SOT. Additionally, we observed an unusual SOT-induced magnetization switching in the Pt/Co/Ta structure, where the switching only responded to applied positive current. The preliminary investigation of this observation is presented in Appendix.

Figure 3-8. SOT-induced magnetization switching behavior of samples $t = 0, 0.9, 3$ nm, measured by the dependence of Hall resistance on the current in the presence of an in-plane bias field of 2 kOe along (a) $+x$ and (b) $-x$ directions.

3.5 Summary

In summary, a Pt layer was inserted between the Co/Ta interface to effectively negate the field-like SOT in perpendicularly magnetized Pt/Co/Pt(t)/Ta structures using AC harmonic Hall voltage measurement technique, as the Rashba effects at the Pt/Co and Co/Pt interfaces counteract each other. The damping-like term is tuned by varying the thickness of the inserted Pt layer to change both sign and magnitude of the SOT

effective fields. The damping-like SOT is zero at $t \approx 2.2$ nm, which is thinner than the bottom Pt layer of 3 nm, indicating the asymmetric contribution from the Pt/Co and Co/Pt interfaces to the damping-like SOT. The magnetic switching direction is found to be controlled by both the orientation of external in-plane magnetic field and the sign of damping-like SOT, which offers additional flexibility in the design of SOT-based spintronic devices.

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Chapter 4. Layer thickness dependence of SOT in Pt/Co/Pt/Co/Ta structures

In this chapter, the investigation of the Co layer thickness dependence of SOT in Pt/Co/Pt/Co/Ta structures with PMA is presented. It is found that the effective fields strength is dependent on the lower Co layer thickness while no changes were observed with varying upper Co layer thickness. The saturation magnetization increases with the lower Co layer thickness, whereas it decreases with the upper Co layer thickness, as the lower Co is sandwiched by two Pt layers and the upper Co is sandwiched by Pt and Ta layers. This asymmetric dependence of the SOT on the two Co layer thicknesses is attributed to the modulations of the saturation magnetization as a result of their interface conditions.

4.1 Motivation

Efficient and accurate magnetization manipulation has always been the focus of the non-volatile magnetic memory and logic devices to attain high speed and power efficiency [1-5]. The novel discovery of STT has revolutionized the manipulation of magnetization via spin current rather than the conventional Oersted field [6-8]. STT acts on the magnetization of an adjacent ferromagnetic “free layer” separated by a

nonmagnetic spacer through the transfer of angular momentum from the “spin polarizer” to the “free layer”. More recently, SOT has been extensively studied in heterostructures composing of either an ultrathin FM contiguous to two HM layers, or having the FM sandwiched between a HM and an oxide layer. Due to its highly efficient magnetization switching [9-11] and fast domain wall motion [12-14], it was proposed for future power-efficient spintronic devices [15,16]. While the mechanism behind efficient SOT switching has yet to be thoroughly explored and optimized, it is potentially superior to STT, as it is not limited by the total spin transfer from the “spin polarizer” [15].

The thickness dependence of either the FM or the HM on the SOT effective fields has been investigated in HM/FM/Oxide heterostructures [17, 18]. Most works of SOT were done in classical HM/FM bilayer, where the thickness of the ferromagnetic material was ~ 1 nm. The ultrathin thickness of FM layer is impractical for real applications. The thickness of the ferromagnetic material can be increased by multi FM layers without changing the properties of the ultrathin FM layer. In Pt/Co/Pt/Co/Ta structures with high thermal stability and strong PMA strength, high speed SOT-driven domain wall motion has been reported. In Pt/Co/Pt/Co/Ta structures with high thermal stability and strong PMA strength, high speed SOT-driven domain wall motion was reported. [19, 20] However, the SOT dependence on the interfacial qualities in the upper and lower Co layers remains unclear. Therefore, SOT is investigated in Pt/Co/Pt/Co/Ta structures as the thickness of the two Co layers are varied. In this chapter, the SOT dependence on the upper and lower Co layer thicknesses in Pt/Co/Pt/Co/Ta structures is studied. In Pt/Co/Pt/Co/Ta structures, the thickness of the lower and upper Co layers contributes PMA behaviors differently, as the lower Co is sandwiched by two Pt layers and the upper Co is sandwiched by Pt and Ta layers. Harmonic Hall voltage measurements reveal that the effective fields decrease with the lower Co layer thickness,

while maintaining at the same level when the upper Co layer thickness was varied. This asymmetric dependence of the SOT on the two Co layer thicknesses is attributed to the modulations of the saturation magnetization as a result of their interface conditions.

4.2 Co layer thickness dependence of PMA

The magnetic thin films were deposited on thermally oxidized silicon wafers using DC magnetron sputtering technique with a base pressure lower than 2×10^{-8} Torr at room temperature. Two sets of film stacks consisting of Ta (3)/ Pt (3)/Co (t_1)/Pt (1)/Co (0.9)/Ta (3) (denoted as A), and Ta (3)/Pt (3)/Co (0.9)/Pt (1)/Co (t_2)/Ta (3) (denoted as B) were prepared, as shown in Figures 4-1(a) and 4-1(b). The as-deposited films were characterized by VSM technique to attain the normalized out-of-plane hysteresis loops of A and B as shown in Figures 4-1(c) and 4-1(d), and in-plane magnetic hysteresis loops of A and B as shown in Figures 4-1(e) and 4-1(f), respectively. Evidential in Figure 4-1, the films exhibited clear PMA. Nonetheless, different effects of t_1 and t_2 on the PMA were observed. With the increase of t_1 , the coercivity increases prominently up till $t_1 = 0.7$ nm, and then decreases as the thickness $t_1 > 0.7$ nm. When t_2 was increased to 1.1 nm, coercivity also increases. Anisotropy field variation for t_1 variation from 0.3 nm to 1.1 nm is also greater than that for the same range of t_2 . The different PMA behaviors contributed by the lower and upper Co layers are attributed to the variation in interface conditions, as the lower Co is sandwiched by two Pt layers and the upper Co is sandwiched by Pt and Ta layers [21-23].

The PMA contributed by Co layer is determined by both thicknesses of Co and its interfaces [21-23]. For the lower Co, the thicknesses of the Pt/Co interface and the Co/Pt interface are assumed as l_{11} and l_{12} . For the upper Co, the thicknesses of the Pt/Co

interface and the Co/Ta interface are assumed as l_{21} and l_{22} . The interface thickness is dependent on the total thickness of layers upon it. For the lower Co thickness t_1 , the effective thickness Δt_1 of Co is $\Delta t_1 = (t_1 + 0.9 - l_{11} - l_{12} - l_{21} - l_{22})$. When the lower Co thickness t_1 increases, only l_{11} increases. However, the increase of l_{11} is smaller than t_1 . As a result, the effective thickness Δt_1 also increases. For the upper Co thickness t_2 , the effective thickness Δt_2 of Co is $\Delta t_2 = (0.9 + t_2 - l_{11} - l_{12} - l_{21} - l_{22})$. When the upper Co thickness t_2 increases, l_{11} , l_{12} , and l_{21} increase. The sum of the increase of l_{11} , l_{12} , and l_{21} will become similar to t_2 . Additionally, the Pt/Co, Co/Pt and Co/Ta interfaces also contribute different PMA. Overall, for the same increase of t_1 and t_2 , the effective thickness Δt_1 and Δt_2 are different, which gives rise to different PMA behaviours.

To quantify the SOT effective fields, the films were patterned into Hall cross structures using the EBL technique and Ar^+ ion etching processes, as introduced in section 2.3. The coordinate system used in this work is schematically illustrated in Figure 4-2(a). θ (θ_H) and φ (φ_H) are the polar and azimuthal angles of the magnetization $\mathbf{M}$ (external magnetic field $\mathbf{H}$) vector, respectively. Figure 4-2(b) shows the SEM image of the fabricated device with electrical measurements configuration. The films were fabricated to $80 \mu\text{m} \times 50 \mu\text{m}$ Hall cross structures with uniform width of $5 \mu\text{m}$. Contact pads composing of Ta (10 nm)/Cu (120 nm)/Au (10 nm) were deposited using a DC magnetron sputtering system. A DC or AC current was applied through the wire along the x -direction and Hall voltage was measured along y -direction throughout the electrical measurements.

Figure 4-1. Schematic of film stacks (a) Ta/Pt/Co (t_1)/Pt/Co/Ta and (b) Ta/Pt/Co (t_2)/Pt/Co/Ta. (c) and (d) out-of-plane hysteresis measurements of the two stacks. (e) and (f) in-plane hysteresis measurements of the two stacks.

Figure 4-2(a) Schematic depiction of fabricated Hall cross structure and definition of coordinate system. θ (θ_H) and ϕ (ϕ_H) are the polar and azimuthal angles of the magnetization $\mathbf{M}$ (external magnetic field $\mathbf{H}$) vector, respectively. (b) Top view of the SEM image of the fabricated device with electrical measurements configuration. (c) Measured AHE loops using a 100 μA DC current for samples $t_l = 0.3$ and 0.7 nm. (d) The variation of AHE resistance R_{AHE} against the Co layer thickness.

Firstly, the AHE loop was measured by detecting the Hall resistances R_H using a 100 μA DC current with a sweeping out-of-plane magnetic field H_z , to characterize the fabricated devices. The measured results show that the fabricated devices maintain PMA, as evidenced by the square AHE loops, as shown in Figure 4-2(c) (for $t_l = 0.3$ and 0.7 nm). The difference in the Hall resistance R_H when the magnetization of the device is pointing along $+z$ and $-z$ orientations, is defined as the AHE resistance R_{AHE} .

in Figure 4-2(c). The obtained values of the AHE resistance R_{AHE} are plotted against the thickness t_1 and t_2 , as shown in Figure 4-2(d). Opposite trends of the AHE resistance R_{AHE} with the increase of the thickness t_1 and t_2 was observed. Different effective thicknesses of Co and its interfaces resulting from the increases of t_1 and t_2 , will lead to different amount of current flowing into Co. Therefore, the opposite trends is primarily due to the amount of current flowing into Co, as increase t_1 and t_2 .

4.3 Characterization of SOT effective fields

The harmonic Hall voltage measurements were performed for both $M_z > 0$ ($\mathbf{M}$ pointing along $+z$ orientation) and $M_z < 0$ ($\mathbf{M}$ pointing along $-z$ orientation) states of each sample, with applied in-plane magnetic field H_x and H_y sweeping in range of ± 700 Oe. The used AC current densities J during the measurements on each device were varied from 1×10^{10} A/m² to 1×10^{11} A/m². Figure 4-3 shows the measured results of the sample $t_1 = 1.1$ nm. The experimental signals of the first harmonic Hall voltage V_{ω} for both $M_z > 0$ and $M_z < 0$ states are shown in Figures 4-3(a) and 4-3(b), as a function of applied external magnetic field H_x and H_y . V_{ω} has a parabolic relationship with H_x and H_y , showing parabolas opening down and up corresponding to $M_z > 0$ and $M_z < 0$ states, respectively. The experimental signals of the second harmonic Hall voltage $V_{2\omega}$ versus H_x and H_y for both $M_z > 0$ and $M_z < 0$ states, are shown in Figures 4-3(c) and 4-3(d). Though $V_{2\omega}$ varies linearly with H_x and H_y , the slope sign is independent on M_z for H_x and dependent on M_z for H_y , respectively. The shown data were measured using AC current density $J = 5 \times 10^{10}$ A/m².

Figure 4-3. The first harmonic Hall voltage signals as a function of external magnetic fields H_x (a) and H_y (b) for both $M_z > 0$ and $M_z < 0$. The second harmonic Hall voltage signals as a function of H_x (c) and H_y (d) for both $M_z > 0$ and $M_z < 0$. The data are shown at AC current density $J = 5 \times 10^{10}$ A/m² for sample $t_l = 1.1$ nm.

The PHE resistance can be obtained by a DC method as introduced in section 2.4.2. However, the sample need to be rotated many times during the measurements. It seems a little difficult and need much time for the two sets of samples. Here, we derive a new method to measure the PHE resistance.

Considering the AC current $I_{AC} = I_0 \sin \omega t$ applied along x -direction, the Hall resistance including both AHE and PHE contributions is expressed as

$$R_H = \frac{V_\omega}{I_0} = \frac{1}{2} R_{AHE} \cos \theta + \frac{1}{2} R_{PHE} \sin^2 \theta \sin 2\phi. \quad (4-1)$$

Here, we assume that the angle of the magnetization is only tilted by the applied magnetic field, implying $\theta = \theta_H$ and $\phi = \phi_H$. For an applied in-plane magnetic field,

$\theta = \theta_H = 90^\circ$. When the longitudinal magnetic field H_x is applied, $\varphi = \varphi_H = 0^\circ$, Eq. (4-1) becomes

$$R_H(\varphi_H = 0^\circ) = \frac{1}{2} R_A \cos \theta. \quad (4-2)$$

When an in-plane magnetic field with $\varphi_H = 45^\circ = \varphi$ is applied, Eq. (4-1) becomes

$$R_H(\varphi_H = 45^\circ) = \frac{1}{2} R_A \cos \theta + \frac{1}{2} R_p \sin^2 \theta. \quad (4-3)$$

Combining Eqs. (4-2) and (4-3), we obtain

$$\xi = \frac{2[R_H(\varphi_H = 45^\circ) - R_H(\varphi_H = 0^\circ)]/R_{AHE}}{1 - [2R_H(\varphi_H = 0^\circ)/R_{AHE}]^2}. \quad (4-4)$$

According to Eq. (4-4), the ratio $\xi = R_{PHE}/R_{AHE}$ can be estimated via measuring two Hall resistances with applied in-plane magnetic fields at $\varphi_H = 0^\circ$ and $\varphi_H = 45^\circ$, since the values of the AHE resistances R_{AHE} have been given in Figure 4-2(d). In this AC method, each sample only need to be rotated once during the harmonic Hall voltage measurements.

Figure 4-4(a) shows the measured Hall resistances R_H as a function of applied magnetic field at $\varphi_H = 0^\circ$ and $\varphi_H = 45^\circ$ for the same sample $t_l = 1.1$ nm. According to Eq. (4-4), we define $Y = 2[R_H(\varphi_H = 45^\circ) - R_H(\varphi_H = 0^\circ)]/R_{AHE}$ and $X = 1 - [2R_H(\varphi_H = 0^\circ)/R_{AHE}]^2$. Then the ratio ξ becomes $\xi = Y/X$. The values of Y and X corresponding to the applied magnetic fields are calculated and plotted in Figure 4-4(b). The ratio ξ is estimated to be ~ 0.2 by the slope of the linear fitting in Figure 4-4(b).

Figure 4-4. (a) The measured Hall resistance R_H versus applied in-plane fields at $\varphi_H = 0^\circ$ and $\varphi_H = 45^\circ$. (b) Plot of $Y = 2[R_H(\varphi_H = 45^\circ) - R_H(\varphi_H = 0^\circ)]/R_{AHE}$ versus $X = 1 - [2R_H(\varphi_H = 0^\circ)/R_{AHE}]^2$. The data are for $t_l = 1.1$ nm sample.

The SOT effective fields of the sample $t_l = 1.1$ nm were determined from Eqs. (2-18)-(2-21) and plotted as a function of the AC current density in Figure 4-5(a) for the damping-like term and Figure 4-5(b) for the field-like term, respectively. The solid symbols represent corrected values while the open symbols represent the uncorrected values for $t = 1.1$ nm sample. Compared to the uncorrected values, the corrected effective fields are ~ 1.4 times larger for the damping-like term and ~ 2.5 times larger for the field-like term, indicating more PHE contribution to the field-like term. The negative damping-like fields are obtained for $M_z > 0$ and positive fields are obtained for $M_z < 0$. For field-like terms, negative values were obtained for both $M_z > 0$ and $M_z < 0$ states. Linear dependence of the effective fields on AC current density is indicated in the range of the current density from 1×10^{10} A/m² to 1×10^{11} A/m². The solid lines are linear fittings to the corrected effective fields. Irrespective of the sign of the effective fields, $\left(\left| dH_{DL(FL)}^+ / dJ \right| + \left| dH_{DL(FL)}^- / dJ \right| \right) / 2$ is defined as the corresponding efficiency χ_{DL} (χ_{FL}), where the $+$ ($-$) sign represents $M_z > 0$ ($M_z < 0$) state. As a result, the effective

fields of $t_l = 1.1$ nm sample are obtained to be ~ 29.7 Oe per 10^{11} A/m² for the damping-like term and ~ 20.1 Oe per 10^{11} A/m² for the field-like term.

Figure 4-5. The effective fields dependence on AC current density for (a) damping-like term and (b) field-like term, including corrected values (solid symbols) and uncorrected values (open symbols). The solid lines are linear fitting to the corrected values. Results of $t_l = 1.1$ nm sample for both $M_z > 0$ and $M_z < 0$ are shown.

4.4 Asymmetric Co layer thickness dependence of SOT

The SOT effective fields of both A and B samples were characterized using the same measurements as the sample $t_l = 1.1$ nm. The efficiency of the effective fields χ_{DL} and χ_{FL} were extracted and plotted as a function of the lower Co layer thickness t_l in Figure 4-6(a), and of the upper Co layer thickness t_2 in Figure 4-6(b), to directly show the dependence of the SOT on the upper and lower Co layer thicknesses. The black and red symbols represent χ_{DL} and χ_{FL} , respectively. The determined damping-like term is larger than the field-like term. It is also observed that the effective fields tend to decrease with the lower Co layer thickness t_l , whereas no obvious changes happen when the upper Co layer thickness t_2 varies from 0.3 nm to 1.1 nm. Moreover,

Figure 4-6. The efficiency of the effective fields plotted with respect to (a) the lower Co layer thickness, and (b) the upper Co layer thickness. The black and red symbols represent χ_{DL} and χ_{FL} , respectively.

the lower Co layer thickness t_l also modulates the difference between the damping-like term χ_{DL} and the field-like term χ_{FL} , which declines from ~ 43.4 Oe per 10^{11} A/m² at $t_l = 0.3$ nm to ~ 9.6 Oe per 10^{11} A/m² at $t_l = 1.1$ nm. The asymmetric Co layer thickness dependence of SOT is primarily due to the different interface conditions of the lower and upper Co layers, as the former is sandwiched by two Pt layers and the latter is sandwiched by Pt and Ta layers.

According to the theory of SHE, the efficiency χ is proportional to $1/(M_S \cdot t_{FM})$ [24-26]. The characterization of as-deposited films finds that the saturation magnetization M_S increases with the lower Co layer thickness t_l , whereas it decreases with the upper Co layer thickness t_u , as shown in Figure 4-7(a). As the Co layer thickness t_l or t_u increasing from 0.3 nm to 1.1 nm, the variation of the saturation magnetization M_S is ~ 526 emu/cc for t_l , which is much larger than its value of ~ 152 emu/cc for t_u . This suggests that the lower Co layer contributes more PMA in the structure. The function of $1/(M_S \cdot t_{FM})$ with respect to the Co layer thicknesses t_l and t_u were plotted in Figure 4-7(b). From Figure 4-7(b), for lower Co layer thickness t_l , $1/(M_S \cdot t_{FM})$ diminishes while the changes of $1/(M_S \cdot t_{FM})$ for the upper Co layer thickness t_u varying from 0.3 nm to 1.1 nm was negligible. The trends of $1/(M_S \cdot t_{FM})$ matches the function relation of the effective fields well, thus demonstrating that there is an asymmetric Co layer thickness dependence of the SOT, which can be attributed to their different interface conditions of the lower and upper Co layers.

Figure 4-7. (a) Plot of the saturation magnetization M_S with respect to the lower and upper Co layer thicknesses. (b) Plot of $1/(M_S t_{FM})$ with respect to the lower and upper Co layer thicknesses.

As explained in Section 4.2, the variation of t_1 and t_2 results in different effective thickness of Co. Moreover, the lower Co is sandwiched by two Pt layers and the upper Co is sandwiched by Pt and Ta layers, leading to different interfaces of the two Co layers. The increase of t_1 and t_2 generates different interfaces conditions. Consequently, the spin current going into Co and the Rashba effect will be different as t_1 and t_2 vary, which contribute the asymmetric dependence of the SOT fields to the two Co layer thicknesses.

The decrease of the saturation magnetization as the upper Co layer thickness t_2 increases, as shown in Figure 4-7(a), seems unusual. This is attributed to the calculation of the saturation magnetization by the equation

$$M_s = \frac{M}{V_{FM}} = \frac{M}{16 \times (t_2 + 0.9)} \times 10^3. \quad (4-5)$$

Here, the unit of M is μemu and unit of t_2 is nm, resulting in M_s with the unit of emu/cc . The raw data are shown in Figure 4-8. The corresponding values of M and M_s are shown in Table 4-1. It is observed that the measured moment M increases with the upper Co layer thickness t_2 , while the saturation magnetization M_s decreases.

The actual saturation magnetization in the structures should be expressed by

$$M_s = \frac{M_1}{16 \times t_2} \times 10^3 + \frac{M_2}{16 \times 0.9} \times 10^3, \quad (4-6)$$

where M_1 and M_2 are the magnetic moments in lower and upper Co layers, respectively. Eq. (4-5) is applicable only if $M_1 = M_2$. Nevertheless, the different values of M_s for $t_1 = t_2$ indicates $M_1 \neq M_2$. It seems that the lower Co layer has larger magnetic moments than upper Co layer for the thickness greater than ~ 0.4 nm.

Therefore, the Eq. (4-5) may be inapplicable. Further work is needed to obtain accurate saturation magnetization.

Figure 4-8. Measured out-of-plane magnetic hysteresis loops for t_2 .

Table 4-1. Summarized values of M and M_s with t_2 .

t_2 (nm)	M (10^{-6} emu)	M_s (emu/cc)
0.3	16.18	842.71
0.5	16.61	741.29
0.7	17.85	697.27
0.9	19.37	672.60
1.1	21.19	662.19

4.5 Summary

In summary, the asymmetric Co layer thickness dependence of SOT in Pt/Co/Pt/Co/Ta structures with PMA was found. In the structures, the lower and upper

Co layers contribute to different PMA behaviors. The saturation magnetization increases with the lower Co layer thickness, whereas it decreases with the upper Co layer thickness. Through the harmonic Hall voltage measurements, it was observed that the effective fields decrease with the lower Co layer thickness variation, while independent on the upper Co layer thickness. The asymmetric Co layer thickness dependence of SOT was attributed to their different interfacial conditions, pointing toward a new methodology in SOT modulation with the potential to enhance the tunability of future magnetic memory and logic devices based on SOT.

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Chapter 5. Field-free SOT-induced magnetization switching in Pt/[Co/Ni]₂/Co/Ta structure

The external in-plane bias field exerted in SOT device restricts its application because it is hard to be integrated in CMOS. In this chapter, we perform the SOT-induced magnetization switching in micron sized Pt/[Co/Ni]₂/Co/Ta structure, as the intrinsic tilt of the magnetization in the device may result in field-free switching. As a result, the field-free SOT switching is observed. Kerr imaging reveals that the field-free SOT switching process is completed via the nucleation of reverse domain and propagation of domain wall in the system. Due to the intrinsic tilt of the magnetization, the nucleated DW adopts a specific DW configuration during the reversal process.

5.1 Motivation

SOT arises from the SHE and the Rashba effect in ultrathin heterostructures comprising of a FM in contact with HM layers [1-4]. Charge current flowing in the HM generates spin current into the FM via SHE, whereas the spin-orbit interaction at the FM/HM interface induces spin accumulation by Rashba effect [3-6]. The SOT-induced

magnetization switching phenomenon [7-12] is capable for free layer control in MRAM, as only an in-plane charge current flow along constructed HM plane is necessary. To realize SOT-induced bipolar magnetization switching in the structure embedded PMA layer, an external in-plane magnetic field is required to break the symmetry along the current direction [13-15]. From a device standpoint, this is not ideal as the limitation of in-plane field in applications influences its integration and scaling.

Numerous techniques have been proposed to execute a field-free SOT-mediated magnetization switching. Lateral structural asymmetries introduced in wedged FM/HM structures were shown to produce a SOT-like switching without the assistance of external field [29, 30]. Tilted magnetic anisotropy adjusted from a wedged FM layer also resulted in bipolar switching of the ferromagnet [31]. More recently, antiferromagnetic (AFM) layers have been incorporated in FM/HM stack as an alternative to the structural modulation. Different stack configurations were investigated using a combination of IrMn and PtMn as AFM layer [19-21]. The in-plane exchange bias field induced by the AFM layer breaks the symmetry [18, 20] and induces a tilting in the out-of-plane magnetization of the FM layer. The AFM layer can substitute as an HM layer in the structure [19]. Another approach is to pin an in-plane FM (iFM) layer with an AFM layer [21]. The structure utilizes that the stray field from the iFM layer affects the magnetization of the FM layer to be switched. The basis of all these techniques is to provide an external stimulus so as to induce an out-of-plane tilt in the magnetization.

In this chapter, we show that by selecting PMA material with a weak out-of-plane anisotropy, bipolar SOT-induced magnetization reversal can be achieved without the assistance of external magnetic field. Our material stack comprises of

Pt/[Co/Ni]_n/Co/Ta thin films, where $n = 2, 3$ and 4 . Bidirectional magnetization switching in the patterned micro Hall bars is observed with an in-plane DC current flow in the structure with $n = 2$. Kerr-microscopy image reveals that the reversal process is completed via nucleation and propagation of a domain wall (DW) in the path of current within the cross structure, which is large enough for domain nucleation and extension mechanism. Due to the intrinsic tilt of the magnetization, the nucleated DW adopts a chiral DW configuration during the reversal process.

5.2 Sample characterization

Stacks comprising of Ta(5 nm)/Pt(5 nm)/[Co(0.25 nm)/Ni(0.5 nm)]_n/Co(0.25 nm)/Ta(5 nm)/Ru(5 nm) films, where $n = 2$ (bilayer), 3 (trilayer) or 4 (four-layer), were grown using DC magnetron sputtering deposition technique. Normalized magnetization hysteresis loops were obtained using polar MOKE technique, as shown in Figure 5-1. The complete film stack structure is illustrated in the inset of Figure 5-1. The coercivity of the bilayer film is 73.5 Oe. A large increase in the film coercivity to 121.7 Oe is observed when n increases to 3. For $n = 4$, the coercivity is almost the same as the trilayer. This is consistent with previous reports of coercivity change with the number layers of Co/Ni. [35] All film stacks exhibit clear PMA as evidenced by the square hysteresis loops with sharp switching. The anisotropy energy density K_u is given by equation $K_u = \frac{1}{2} M_s \bullet H_s$. The saturation magnetization M_s and the hard axis saturation magnetic field H_s were measured by VSM. The corresponding values are: $M_s = 539 \text{ emu/cm}^3$ and 609 emu/cm^3 for $n = 2$ and 4 ; $H_s = 924.4 \text{ Oe}$ and 4715.6 Oe for $n = 2$ and 4 , respectively. The out-of-plane anisotropy energy density was calculated

to be 2.5×10^5 erg/cm² for $n = 2$, increasing to 1.4×10^6 erg/cm² for $n = 4$, via the hard axis measurement method. The film stacks were patterned into cross-shaped structures, comprising of a wire and an orthogonal Hall bar, using a combination of EBL and Ar⁺ ion milling techniques, as introduced in section 2.3.

Figure 5-1. Normalized magnetization hysteresis loops measured using polar MOKE magnetometer. Inset shows schematic of Pt/[Co/Ni]_n/Co/Ta thin film stack structures with $n = 2, 3$ and 4.

5.3 SOT effective fields in Pt/[Co/Ni]_n/Co/Ta structures

Harmonic Hall voltage measurements were performed to quantify the SOT effective fields of the fabricated devices. Figures 5-2(a)-(e) show the experimental results. We calculate the effective fields $H_L = -23$ Oe and 21 Oe for up and down

magnetization, respectively, and $H_T = 19.80$ Oe and 19.20 Oe for up and down magnetization, respectively.

The SOT effective fields of the different film stacks ($n = 2, 3$ and 4) are shown in Figures 5-3(a) and 5-3(b), as a function of the AC current density. A linear dependence of the effective fields on current density is obtained. The positive and negative damping-like effective fields correspond to the magnetization orientation with respect to the initial up (+z) and down (-z) magnetization states, respectively, as shown in Figure 5-3(a). The field-like effective fields for initial up and down magnetized states have the same sign and amplitude as seen from Figure 5-3(b). This is consistent with

Figure 5-2. Harmonic Hall voltage signals. (a) The AHE loop obtained by AC measurement. (b) First Harmonic signals with H_x . (c) First Harmonic signals with H_y . (d) Second harmonic signals with H_x . (e) Second harmonic signals with H_y .

Figure 5-3. (a) Damping-like effective fields of each sample for $+z$ and $-z$ magnetized states as a function of current density. (b) Field-like effective fields for each sample for $+z$ and $-z$ magnetized states as a function of current density.

the field-like effective fields being independent of the magnetization orientation. The plots reveal a negative correlation between the FM layer thickness and the SOT effective fields. The bilayer sample exhibits much larger SOT fields as compared to the four-layer sample. For the bilayer sample, the damping-like effective fields increases by ~ 50 Oe as the current is increased from 1 mA to 5 mA, whereas for the four-layer sample, the increase is only ~ 20 Oe for the same current range.

5.4 Field-free magnetization switching induced by SOT

To investigate the SOT effect on the magnetization reversal process, the AHE measurements was conducted using different magnitude of AC bias current. Shown in Figures 5-4(a), 5-4(b) and 5-4(c) are the measured respective AHE loops for wires with film stack $n = 2, 3$ and 4 , respectively. The switching field decreases as the bias current

is increased. The corresponding switching fields extracted from the AHE loops, as a function of the AC bias current amplitude for stacked wire $n = 2, 3$ and 4 , are presented in Figure 5-4 (d). For $n = 2$ and 3 , the coercivity of the wire decreases linearly with respect to the applied current. A striking observation is that the coercivity of the stacked wire $n = 2$ is almost zero when the amplitude of the applied AC bias current is ≥ 3 mA. For the wire with $n = 4$, there is negligible change in the coercivity for current smaller than 3 mA. For current amplitude greater than 3 mA, the coercivity decreases linearly with current.

Figure 5-4. Representative AHE loops measured by different AC bias current for samples (a) $n = 2$, (b) $n = 3$, and (c) $n = 4$. (d) Measured coercivity as a function of the magnitude of the applied current for wire patterned with film stacks with $n = 2, 3$, and 4 .

The measurements were performed using a DC bias current on the structures with $n = 2$ structures and are presented in Figure 5-5. In general, the coercivity decreases as the magnitude of the DC current increases and for $I_{DC} > 3\text{mA}$, the coercivity is almost zero. For DC current magnitude smaller than 3mA, the positive and negative DC bias current lead to different coercivity trends. Similar change in coercivity as a function of DC current bias have been reported in structures comprising of HM/FM layer and the decrease in coercivity has been attributed to the damping-like SOT fields induced by the current [19]. For all measurements, the current density in the wire was in the range of 10^{10} A/m^2 .

To assess the Joule heating effect, the resistance of the wire was monitored by a DC current flow for 10 minutes. Figure 5-6 shows the measured wire resistance for $n = 2$ structures by 1mA and 3 mA, respectively. Though the variation of resistance at a fixed DC bias is $\sim 0.1 \Omega$, a change of $\sim 1 \Omega$ was observed in the resistance of $n = 2$ sample as the current is increased from 1 mA to 3 mA, where the coercivity is tuned by current. Therefore, the Joule heating assists on the reversal process. No similar change was observed for the $n = 4$ sample, as shown in Figure 5-6. As such, the coercivity trend observed for $n = 2$ structures can be attributed to a combination of joule heating and SOT-induced switching. For the $n = 4$ sample, no change in the wire resistance was observed as the DC bias was increased, as shown in Figure 5-6. As such, the coercivity trend observed for $n = 2$ structures can be attributed to a combination of joule heating and SOT-induced switching. As such, the coercivity trend observed in our structures can be attributed to a combination of Joule heating and SOT-induced switching. We note that the coercivity decrease correlates with the corresponding measured SOT fields. The onset of coercivity change occurs when the damping-like SOT fields is greater than 15 Oe. This corresponds to a current of 0.5 mA for the bilayer sample and 3 mA for the

four-layer sample. The coercivity of the bilayer sample reduces to zero for damping-like SOT field greater than 30 Oe.

Figure 5-5. AHE loops measured by positive (a) and negative (b) DC current for $n = 2$ structures. (c) Coercivity trends on DC and AC current.

Figure 5-6. The wire resistance monitored by DC current flow for 10 minutes. (a) The wire resistance measured by 1mA and 3 mA for $n = 2$ structures. (b) The wire resistance measured by 3 mA and 5 mA for $n = 4$ structures.

To confirm the observed SOT switching, Hall resistance (R_H) measurements with DC current sweeping were performed on the $n = 2$ structure, without any externally applied magnetic fields. Figure 5-7 shows the measured R_H as a function of the DC current. A clear hysteresis loop was obtained, implying a deterministic switching of the magnetization induced by the applied current. Firstly, the magnetization is aligned along the $+z$ orientation. No change in R_H is observed when positive current (along $+x$ direction) flows through the wire. As the current is swept in the opposite direction, negative current (along $-x$ direction), R_H exhibits a step wise decrease at a current of -4 mA, reaching saturation at -6.5 mA. This implies that the magnetization has switched to the $-z$ orientation. As the current is then increased towards $+6.5$ mA, the initial change in R_H signal occurs at 2 mA, with a quasi-stable state at $+3$ mA and saturation at $+4$ mA. This results in an asymmetric hysteresis loop, as shown by the black loop in Figure 5-7. This asymmetric switching is due to an initial large current required to nucleate a reverse domain. The change in the Hall resistance corresponds each run, a clear hysteretic loop is obtained, indicating that the switching process is deterministic in nature.

Figure 5-7. Measured R_H as a function of DC current without external magnetic field for Pt/[Co/Ni]₂/Co/Ta structure.

5.5. Switching process revealed by Kerr imaging

Direct observation of the magnetization switching process was carried out using quasi-static Kerr imaging technique. The sample was first saturated along the $+z$ direction and the field was reduced to zero. This initial state was captured and used as a reference to be subtracted from subsequent images captured at different DC bias. Figure 5-8 shows the Kerr images at different instances during the switching process, corresponding to the state labelled in Figure 5-7. The wire was initially saturated by a large magnetic field along the $+z$ direction. The initial configuration, image A was captured after a positive current of +6.5 mA was applied to the wire. No change in magnetization configuration is observed. As the current was reduced from +6.5 mA to -4 mA, a reversed domain is nucleated in the wire, as evidenced by the bright contrast

Figure 5-8. Kerr images at different stages during the reversal process. Image A shows the initial up (+z) state; images B1-B4 show the gradual reversal process from up to down (-z) state; image C shows that the magnetization has completely switched to the down state; image D shows the quasi stable state as the magnetization is reversed in the opposite direction; image E shows that the magnetization has switched back to the up state again. The yellow arrows show the corresponding current directions.

in Figure 5-8-B1, indicating the onset of magnetization switching. The magnetic configuration at the top half of the wire has flipped to the down ($-z$) state. Further increase of the current leads to the expansion of the reversed domain along both the wire length as seen in Figure 5-8-B2→B4. Complete magnetization reversal of the wire was achieved when the current was increased to -6.5 mA, as can be seen by the complete white contrast of the structure in Figure 5-8-C. As the current was increased from -6.5 mA to $+2$ mA, the quasi stable region in the Hall signal, Figure 5-7, corresponds to the pinning of the DW at the Hall cross as seen in Figure 5-8-D. As the current was increased to positive saturation at $+6.5$ mA, the magnetization switched towards the up ($+z$) state again, as seen in Figure 5-8-E. The Kerr imaging confirms that the reversal process is completed via DW nucleation and propagation within the structure. The current can deterministically switch the magnetization orientation of the wire. Different orientations of current flow lead to different stable magnetization configurations.

Reversed domain nucleating from the edge of the wire has been reported by a combination of Oersted field and weakened anisotropy at the edges due to defects. [22] The out-of-plane component of the Oersted field has the maximum amplitude $H_{z-Oersted}$ at the wire edges. [23] For a uniform strip conductor with width w and thickness t , $H_{z-Oersted}$ can be approximated as $H_{z-Oersted} = Jt(3 + 2\ln(w/t)) / 4\pi$ when $t \ll w$. [24] In our geometry, the conductor can be considered as a $5 \mu\text{m}$ wide and 20 nm thick strip. The Oersted field is estimated to be $\sim 0.84 \text{ mT}$ for a current of 3 mA (current density $J = 1 \times 10^{10} \text{ Am}^{-2}$), where the reversed domain is nucleated. This is much smaller than corresponding SOT fields at 3 mA which is $\sim 30 \text{ Oe}$. To show that the combination of Oersted field and weak-end anisotropy due to edge-defects do not play a role in the

switching, the reversed process was repeated for initial magnetization along $+z$ and $-z$ directions. Figure 5-9 shows that though the reversal starts from the edge of the wire, the region where the reversed domain nucleates are different. For each instance, the reversed domains are nucleated closer to the contact where the current is applied. This implies that the Oersted field and edge-defects do not play a significant role in the reversal domain nucleation.

Figure 5-9. The reversal occurs from the edge for initial magnetization along (a) $+z$ and (b) $-z$ directions. The two configurations occur at opposite current directions.

5.6 Insight to the switching process

The deterministic SOT switching is ascribed to a tilt in the out-of-plane magnetization induced by the combination of Joule heating and SOT in the bilayer structure. To experimentally assess this presumptive explanation, a small out-of-plane magnetic field was applied and the in-plane current sweeping measurements on samples

Figure 5-10. Measured R_H as a function of the DC current with a small fixed out-of-plane magnetic field along the $+z$ or $-z$ directions for (a) up and (b) down initial magnetization states. (c) and (d) are the schematic magnetic configurations corresponding to (a) and (b), respectively.

with magnetization along the $+z$ orientation was performed. When the out-of-plane field of 12 Oe was applied along the $+z$ direction, no magnetization switching behavior was observed in the measured AHE signal, even for current strength up to 10 mA, as indicated by the black data line in Figure 5-10(a). However, when the field (-16 Oe) direction was reversed, *i.e.* along the $-z$ direction, which was also opposite to the magnetization orientation, a sharp change in the AHE signal was observed, implying the switching of the magnetization state, as shown by the red data line in Figure 5-10(a). Once the magnetization switches, it was aligned with the applied field direction, and no further switching was observed even when the current direction was reversed. Similar behavior was observed when the initial magnetization of the device is set along the $-z$ orientation, as shown in Figure 5-10(b). These experimental results confirm our explanation that the marginal tilt of the magnetization with respect to the z -axis in the bilayer structure contributes to the field-free SOT reversal process. As introduced in section 5.2, the out-of-plane anisotropy energy rapidly increases when the Co/Ni repeat times n increases, implying stronger coupling of Co and Ni for larger n . The magnetization tilt originates from the weak coupling of Co and Ni for $n = 2$. Nevertheless, the size of the magnetization tilt is too small to characterize. For $n = 2$ and $n = 4$, stronger coupling of Co and Ni results in negligible magnetization tilt. Figures 5-10(c) and 5-10(d) depict the configurations of current induced SOT fields for initial magnetization along $+z$ and $-z$ directions, corresponding to Figures 5-10(a) and 5-10(b) respectively. The direction of the transverse effective field H_T is determined by $\hat{z} \times \vec{J}$, which is independent of the initial magnetization state. The direction of the longitudinal effective field H_L is determined by $\hat{m} \times \hat{s}$, where $\hat{m}$ is the magnetization direction and $\hat{s}$ represents the average spin direction of the electrons diffusing into the magnetic layer.

In our configurations, the collective spin Hall effect from Pt underlayer and Ta capping layer results in a positive spin Hall angle, which aligns $\hat{s}$ pointing to $-(\hat{z} \times \vec{J})$. Therefore, the direction of the longitudinal field is determined by $-(\hat{m} \times (\hat{z} \times \vec{J}))$, which is dependent of the initial magnetization state, as shown in Figures 5-10(c) and 5-10(d).

Figure 5-11. The R_H vs I_{DC} loops with different applied longitudinal external magnetic fields along (a) $+x$ and (b) $-x$ directions.

To gain an insight into the SOT induced DW motion leading to the magnetization switching, R_H measurements were carried out by sweeping DC current with various fixed in-plane magnetic fields (H_x) applied along the wire long axis. The measured R_{AHE} vs I_{DC} loops at different H_x are shown in Figure 5-11. Irrespective of the magnitude of the negative H_x , complete magnetization reversal at the Hall cross is obtained, as evidenced by the maximum change in R_H magnitude. For positive H_x less than 500 Oe, a smaller change in R_H magnitude is obtained, implying incomplete switching at the Hall cross. As the positive H_x is increased, the change of R_H in magnitude increases correspondingly, reaching the saturation for $H_x \geq 500$ Oe. Our result is consistent with

Pt being the dominant source of DMI and leading to a negative DMI effective field H_{DMI} , stabilizing in a left-handed Néel DW.

Figure 5-11 infers that the negative field can result in the full reversal at the Hall cross evidenced by the maximum change in R_H magnitude. Whereas for the positive field, the full switching at the Hall cross only occurs when the field is larger than 500 Oe. For the positive field smaller than 500 Oe, the Hall cross can be reversed only partially evidenced by the lower change in R_H magnitude. Therefore, the DMI effective field H_{DMI} in our sample structure is negative, acting along the $-x$ orientation. Negative H_{DMI} results in a left-handed Néel DW chirality. This is consistent with Pt being the dominant source of DMI.

The representative loops for $H_x = +500$ Oe and -100 Oe are shown in Figure 5-12(a). For the measured R_H - I_{DC} loops with fields applied along the $+x$ (+500 Oe) or $-x$ (-100 Oe) orientations in Figure 5-12(a), complete magnetization switching at the Hall cross is obtained. Despite both field orientations displaying clear hysteresis, the switching behavior is completely different. When a positive H_x is applied, a R_H - I_{DC} loop similar to the result without any applied external field was obtained. However, when the applied H_x is along the $-x$ -direction, the magnetization switching from $+z$ to $-z$ direction occurs when a positive current was applied. The discrepancy is attributed to the stabilization of different DW configurations with the application of H_x . The direction of the H_x favors a handedness chirality of the DW mediating the reversal process. For H_x applied along the $+x$ orientation more than +500 Oe, a right-handed Néel DW is obtained. It is known that for SOT-induced Néel DW motion in structure with Pt underlayer, the left-handed DW moves along the direction of current, whereas

the right-handed DW moves in the opposite direction of current. This is consistent with the measured R_H - I loops property shown in Figure 5-12(a).

Figure 5-12. (a) R_H - I loops measured by sweeping DC current with a fixed in-plane magnetic field along the (black) $+x$ and (red) $-x$ directions. (b) Measured R_H - I loops with sweeping DC current when a fixed in-plane magnetic field was applied along the (red) $+y$ and (blue) $-y$ directions together with the loop for (black) zero field.

Similar measurements were conducted with an in-plane transverse field. Figure 5-12(b) shows the representative R_H - I loops in the presence of the transverse field along the $+$ or $-y$ -directions. It is worth noting that the transverse field does not affect the switching behavior and the magnitude of current required to induce switching. Additionally, irrespective of the field orientation, the same switching behavior implies that the magnetization reversal process is mediated by the damping-like term of the SOT.

5.7 Summary

In summary, field-free bipolar SOT-induced magnetization switching can be achieved by a weak out-of-plane magnetic anisotropy in as grown Pt/[Co/Ni]₂/Co/Ta structures. Kerr imaging reveals that the reversal process is completed *via* the nucleation and propagation of DW within the wire. Due to the intrinsic tilt of the magnetization, the nucleated DW adopts a specific DW configuration during the reversal process. These results may pave the way for an alternative approach to induce field-free SOT-induced magnetization switching.

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Chapter 6. Conclusion and future work

6.1 Conclusion

In this thesis, we detail the investigations on the SOT effective fields and SOT-induced magnetization switching in ferromagnetic multilayer structures. The SOT effective fields are quantified using AC harmonic Hall voltage measurement technique. Strong SOT including both the damping-like and field-like terms is obtained in Pt/Co/Ta structure with PMA, contributed by the opposite spin Hall angles of Pt and Ta. A Pt layer inserted between the Co/Ta interface can effectively negate the field-like SOT in Pt/Co/Pt (t)/Ta structures, as the Rashba effects at the Pt/Co and Co/Pt interfaces counteract each other. The damping-like term is tuned by varying the thickness of the inserted Pt layer to change both the sign and magnitude of the SOT effective fields. The damping-like SOT is zero at $t \approx 2.2$ nm, which is thinner than the bottom Pt layer of 3 nm, indicating the asymmetric contribution from the Pt/Co and Co/Pt interfaces to the damping-like SOT.

In the Pt/Co/Pt/Co/Ta structure, the two Co layers contribute to different PMA due to their interface conditions. By varying either the lower or the upper Co layer thickness, it is found that the effective field strength is dependent on the lower Co layer thickness while no changes were observed with varying upper Co layer thickness. The asymmetric dependence of the SOT on the two Co layer thicknesses is attributed to the modulations of the saturation magnetization as a result of their different interface conditions.

From the device standpoint, the field-free capability of SOT-device is demanded. The external in-plane bias field exerted in SOT device restricts its application because it is hard to integrate in CMOS. The micron sized Pt/[Co/Ni]₂/Co/Ta structure is studied to achieve the field-free SOT switching due to the intrinsic tilt of the magnetization in the device. Kerr imaging reveals that the field-free SOT switching process is completed via the nucleation of reverse domain and propagation of domain wall in the system. Due to the intrinsic tilt of the magnetization, the nucleated DW adopts a specific DW configuration during the reversal process.

6.2 Future work

6.2.1 Enhancing SOT by engineering different capping layers

As discussed in chapter 3 and chapter 4, the interface conditions of the FM are also important for SOT. The Co layer sandwiched between Pt and Ta layers induces stronger SOT than that sandwiched between two Pt layers. Even in the Pt/Co/Pt/Co/Ta structure, where Pt/Co/Pt is coupled with Pt/Co/Ta, the lower and upper Co layers contribute to different SOT. Therefore, different capping layers can be tried on a HM/FM bilayer when we optimize the stack structure for larger SOT. SOT and DMI have been investigated in Pt/Co/[Ni/Co]₄/X with different capping layers (X = Pt, Ta, MgO, or Cu) by J. Yu, et. al. [1]. The result provides an insight into the role of DMI in SOT driven magnetization switching, demonstrating the feasibility of achieving desirable SOT and DMI for spintronic devices. Y. C. Lau evaluated the SOT efficiency in in-plane magnetized HM/CoFeB/MgO heterostructures (HM = Pt, W, and Ta), suggesting that a more advanced model is required to accurately describe SOT effective fields. [2]

However, the mechanism behind still needs more works to investigate. Moreover, the AFM is never used in these works. Therefore, Pt, Ta, Cu, IrMn, and MgO can be selected as the capping layers on Pt/Co bilayer. The primary results of IrMn and Cu capping layers are shown in Figure 6-1 and Figure 6-2. The results show that IrMn capping layer can generate larger damping-like SOT, where the field-like terms are comparable for both capping layers.

Figure 6-1. The measured SOT effective fields for IrMn capping layer.

Figure 6-2. The measured SOT effective fields for Cu capping layer.

6.2.2 Investigating SOT switching in Pt/Co/Ta structure

SOT-induced magnetization switching in FM/HM heterostructures has attracted extensive attention because of its prospects in low power magnetic memories and logic

devices [3-7]. In most reports, the magnetization switching between $M_z > 0$ and $M_z < 0$ states was achieved by opposite current. [3, 7, 8] The SOT switching process can be explained by the combination of the SHE and DMI, where a sufficient in-plane bias field collinear with the applied current to overcome DMI is needed. [7-11] As presented in Chapter 3, it was observed that the switching only responded to applied positive current in the SOT-induced magnetization switching under in-plane bias field $H_x = \pm 2$ kOe in the perpendicularly magnetized Pt/Co/Ta structure, as shown in Figure 6-3. The unusual SOT switching in the Pt/Co/Ta structure cannot be explained by the theory of the SHE and DMI. Therefore, the further investigation of the SOT switching in the perpendicularly magnetized Pt/Co/Ta structure is needed in future work. The roles of the in-plane bias field and DC current in the switching process should be explored. The dependence of SOT switching on the in-plane bias field should be studied. Moreover, the switching process can be revealed by Kerr imaging.

Figure 6-3. SOT-induced magnetization switching with applied in-plane bias field (a) $H_x = +2$ kOe and (b) $H_x = -2$ kOe in Pt/Co/Ta structure.

The AHE measurements were performed using various DC currents with applied an external in-plane magnetic field, to investigate the roles of the in-plane bias field and

DC current in the switching process. Figures 6-4(a) and 6-4(b) show the measured AHE loops by a 100 μA DC current, which has a negligible effect on the magnetization switching, with applied positive and negative in-plane bias fields H_x , respectively. The AHE resistance R_{AHE} remains the same value of $\sim 1 \Omega$ for various in-plane bias fields. The square shape of the AHE loops demonstrates that the magnetization in the magnetic layer is switched uniformly by the out-of-plane magnetic field. From the AHE loop in the inset of Figure 3-3(a), the measured positive and negative values of the Hall resistance R_H represent the $-z$ and $+z$ magnetization, respectively. The switching fields which switch the magnetization to $+z$ and to $-z$, are defined as H_{SW}^+ and H_{SW}^- . Therefore, the coercivity (H_C) of the device can be expressed as $H_C = (H_{\text{SW}}^+ - H_{\text{SW}}^-)/2$. The hysteresis loop center $H_0 = (H_{\text{SW}}^+ + H_{\text{SW}}^-)/2$ can be used to characterize the horizontal shift of the hysteresis loop. For the in-plane bias field of ± 500 Oe, the coercivity of the device is around 20 Oe. For the in-plane bias field of ± 2000 Oe, the coercivity reduces to about 7 Oe. The decrease in the coercivity with increasing in-plane bias field suggests that the in-plane bias field allows the magnetization to be switched more easily. Meanwhile, the shift in the switching field $\Delta H_{\text{SW}}^+ = [H_{\text{SW}}^+ (500 \text{ Oe}) - H_{\text{SW}}^+ (2000 \text{ Oe})]/2$ is larger than $\Delta H_{\text{SW}}^- = [H_{\text{SW}}^- (500 \text{ Oe}) - H_{\text{SW}}^- (2000 \text{ Oe})]/2$ for the positive in-plane bias field as shown in Figure 6-4(a). However, the in-depth physics of the in-plane bias field affecting the AHE loops remains unclear, which needs future efforts to search.

Figures 6-4. Measured AHE loops by a 100 μ A DC current with the positive (a) and negative (b) in-plane bias field H_x .

Figure 6-5 shows the measured results for various positive currents with an in-plane bias field of $H_x = +2$ kOe. With the application of increasing DC currents, the switching fields H_{SW}^+ and H_{SW}^- become similar due to the small coercivity of the device. The shape of the AHE loops also becomes step-wise, containing a series of intermediate Hall resistance and implies the existence of domains in the Hall cross area. [12] These domains can be switched individually to achieve the full switching in response to large enough applied fields to align all domains. The results illustrate that the DC current can modulate the mode of the magnetization switching with the assistance of an in-plane bias field.

Figure 6-5. Out-of-plane magnetic field dependence of the Hall resistance R_H measured by various positive currents with applied in-plane bias field $H_x = +2$ kOe.

Though the effects of the in-plane bias field and DC current were observed in Figures 6-4 and 6-5, SOT-induced magnetization switching should be investigated by measuring DC current dependence of the Hall resistance R_H with applied an in-plane bias field. During the SOT switching measurements, the effects of the initial magnetization state and DC current sweep way were also studied. It was found that the initial magnetization state and the DC current sweeping sequence also affect the SOT switching process under small in-plane bias fields. When the in-plane bias field is large enough to overcome the DMI, the effects of the initial magnetized state and the DC current sweep sequence can be ignored. The in-depth physics will also be researched in future. Additionally, Kerr imaging will be used to reveal the switching process. The

preliminary investigation of the SOT switching in the perpendicularly magnetized Pt/Co/Ta structure is presented in Appendix.

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Appendix. Unusual magnetization switching induced by SOT in Pt/Co/Ta structure

As mentioned in chapter 3, the magnetization switching induced by SOT in perpendicularly magnetized Pt/Co/Ta structure is studied in the Appendix. The AHE measurements using various DC currents with applied an external in-plane magnetic field were performed to reveal the roles of the in-plane bias field and DC current in the magnetization switching process. Unusual switching behavior where switching only occurs in response to positive current, is observed in the structure. The phenomenon is attributed to the field-like SOT, which shifts the hysteresis loop acting as a magnetic field along $-y$ -orientation. The initial magnetization and DC current sweep sequence are found to result in different SOT-induced magnetization switching process. For small in-plane bias fields, they can affect the mode of switching, which can be ignored when the in-plane bias field is large enough to overcome the DMI.

A.1 Motivation

SOT-induced magnetization switching in magnetic/heavy metal multilayers has attracted extensive attention because of its prospects in low power magnetic memories and logic devices. [1-5] In these multilayer structures, SOT originates from both the SHE [6-8] and the Rashba effect [9-11]. Most studies have reported that SHE plays a more important role as compared to the Rashba effect in SOT-induced magnetization switching. [12-15] According to SHE, the spin dependent scattering in heavy metals causes a perpendicular spin current when an in-plane charge current is applied. The spin current then exerts a torque on the magnetic moment of the ferromagnetic layer adjacent to heavy metal layer to induce the magnetization switching. In MRAM, SOT-induced magnetization switching by using an in-plane current is preferred over conventional spin transfer torque, as the former avoids having a large switching current through a MRAM cell. [16-19] To realize SOT-induced magnetization switching in the structure with PMA, an external in-plane magnetic field is required to break the symmetry along the in-plane current direction. [3, 4, 20, 21] Therefore, it remains important to understand the roles of the in-plane bias field in SOT-induced magnetization switching, even though field-free SOT switching has been achieved via different techniques. [22-26]

A macrospin model was first used by Liu *et. al.* to explain how an in-plane bias field breaks the symmetry in the response to SHE-torque. [12] In case of small spin torques, the bias field was shown to favor either one of the out-of-plane magnetization orientation ($\pm M_z$), depending on its sign. Nevertheless, the model only applies to a uniform switching process. The SOT-driven domain wall (DW) depinning and domain expansion model proposed by Lee *et al.*, gave a better understanding of the switching

process in more complex magnetization systems. [13] In this model, the switching process can be explained by a SHE+DMI scenario, where a sufficient in-plane bias field collinear with the applied current to overcome DMI is needed. The magnetic moments within the DW is significantly oriented by the in-plane bias field, resulting in a component parallel to the current. This allows the expansion of a reversed domain via an effective perpendicular field produced by SHE-torque to induce a full magnetization switching.

The SOT-induced magnetization switching behaviors in Pt/Co/Ta structure with PMA are investigated. The roles of the in-plane bias field and DC current in the magnetization switching process are revealed by the AHE measurements using various DC currents with applied an external in-plane magnetic field. Unusual switching behavior where switching only occurs in response to positive current, is observed in the structure. The phenomenon is attributed to the field-like SOT, which shifts the hysteresis loop acting as a magnetic field along $-y$ -orientation. The initial magnetization and DC current sweep sequence are found to result in different SOT-induced magnetization switching process. For small in-plane bias fields, they can affect the mode of switching, which can be ignored when the in-plane bias field is large enough to overcome the DMI.

A.2 The roles of in-plane bias field and current in SOT-induced magnetization switching

To understand the role of the in-plane bias field in SOT-induced magnetization switching, the AHE measurements were performed with the assistance of an external

in-plane magnetic field using a 100 μA DC current, which has a negligible effect on the magnetization. Figures A-1(a) and A-1(b) show the measured AHE loops with applied positive and negative in-plane bias fields H_x , respectively. The AHE resistance R_{AHE} remains the same value of $\sim 1 \Omega$ for various in-plane bias fields. The same square shape of the measured AHE loops demonstrates that the magnetization in the Hall cross area of the magnetic layer is switched uniformly by the out-of-plane magnetic field. The result implies that the in-plane bias field cannot affect the mode of the magnetization switching by itself. From the AHE loop in the inset of Figure 3-3(a), the measured positive and negative values of the Hall resistance R_H represent the $-z$ and $+z$ magnetization, respectively. The switching fields which switch the magnetization to $+z$ and to $-z$, are defined as H_{SW}^+ and H_{SW}^- . Therefore, the coercivity (H_C) of the device can be expressed as $H_C = (H_{\text{SW}}^+ - H_{\text{SW}}^-)/2$. The hysteresis loop center $H_0 = (H_{\text{SW}}^+ + H_{\text{SW}}^-)/2$ can be used to characterize the horizontal shift of the hysteresis loop. For the in-plane bias field of ± 500 Oe, the coercivity of the device is around 20 Oe. For the in-plane bias field of ± 2000 Oe, the coercivity reduces to about 7 Oe. The decrease in the coercivity with increasing in-plane bias field suggests that the in-plane bias field allows the magnetization to be switched more easily. Meanwhile, the shift in the switching field $\Delta H_{\text{SW}}^+ = [H_{\text{SW}}^+(500 \text{ Oe}) - H_{\text{SW}}^+(2000 \text{ Oe})]/2$ is larger than $\Delta H_{\text{SW}}^- = [H_{\text{SW}}^-(500 \text{ Oe}) - H_{\text{SW}}^-(2000 \text{ Oe})]/2$ for the positive in-plane bias field as shown in Figures A-1(a), which suggests that the positive in-plane bias field has more effect on the magnetization switching to $+z$ -orientation. The opposite result in Figures A-1(b) indicates that the negative in-plane bias field has more effect on the magnetization switching to $-z$ -orientation. As a result, the horizontal shift of the hysteresis loop is affected by the direction of in-plane bias field, with the signs of H_0 depending on H_x .

Figure A-1. Measured AHE loops by a 100 μ A DC current with the positive (a) and negative (b) in-plane bias field H_x of 500 Oe and 2000 Oe.

Various DC currents I_{DC} between -4.9 mA and $+5.1$ mA with the step size of 1 mA, were then used to perform the AHE measurements with the assistance of an in-plane bias field. Figures A-2(a) and A-2(b) show the measured results for various positive

currents with an in-plane bias field of $H_x = +2$ kOe and $H_x = -2$ kOe. Measurements obtained by using negative currents are shown in Figures A-2(c) and A-2(d). With the application of increasing DC currents, the switching fields H_{SW}^+ and H_{SW}^- become similar due to the small coercivity of the device. The shape of the AHE loops also becomes step-wise, containing a series of intermediate Hall resistance and implies the existence of domains in the Hall cross area. [27] These domains can be switched individually to achieve the full switching in response to large enough applied fields to align all domains. Larger magnitude of applied current leads to more domains which require greater H_z to switch, as evidenced by the increased shift of the hysteresis loop with enhance applied current in Figure A-2. Interestingly, all switching behaviors for positive or negative currents with an in-plane bias field happen corresponding to the same direction of applied out-of-plane magnetic fields, which is determined by the sign of $H_x \times I_{DC}$. As shown in Figures A-2(a) and A-2(d), the same results (switching happens in area of $H_z > 0$) were obtained for positive currents with positive in-plane bias field and negative currents with negative in-plane bias field. Similarly, Figures A-2(b) and A-2(c) show the same results (switching happens in area of $H_z < 0$), which is opposite to Figures A-2(a) and A-2(d), due to the different signs of the currents and the in-plane bias field. The results illustrate that the DC current can modulate the mode of the magnetization switching with the assistance of an in-plane bias field, and acts as an equivalent out-of-plane field, the direction of which is opposite to the sign of $H_x \times I_{DC}$.

Figure A-2. Out-of-plane magnetic field dependence of the Hall resistance R_H with applied in-plane bias field $H_x = +2$ kOe (a) and (c), and $H_x = -2$ kOe (b) and (d), for various constant currents.

The measurements with applied in-plane fields along y -orientation (H_y) were also performed. It is found that only the direction of H_y can affect the magnetization switching. The results with an in-plane field of $H_y = +2$ kOe are shown in Figures A-3(a) and A-3(c) for various positive and negative currents, respectively. Figures A-3(b) and A-3(d) show the measured results for applied in-plane field of $H_y = -2$ kOe. Different with the case of H_x , square hysteresis loops are obtained even though the coercivity almost equals zero. As shown in Figures A-3(a) and A-3(c), the same results (switching happens in area of $H_z < 0$) were obtained for positive in-plane field H_y . Similarly, Figures A-3(b) and A-3(d) show the same results (switching happens in area of $H_z > 0$), which is opposite to Figures A-3(a) and A-3(c), due to the opposite direction of applied in-plane field H_y . The shift of the hysteresis loops is only dependent on the

direction of H_y , irrespective of both the magnitude and sign of the current. The result indicates that the DC current has no effect on the magnetization switching when an in-plane field along y -orientation is applied.

Figure A-3. Out-of-plane magnetic field dependence of the Hall resistance R_H with applied in-plane bias field $H_y = +2$ kOe (a) and (c), and $H_y = -2$ kOe (b) and (d), for various constant currents.

A.3 Determination of SHE-torque

According to the performed AHE measurements by various DC currents with fixed in-plane magnetic fields, the spin Hall torque efficiency χ_{SHE} can be estimated. [14, 15]

In this method, the effective field induced by SHE is defined by $H_{eff}^z = \chi J = H_0$.

Therefore, the values of $H_{eff}^z = (H_{SW}^+ + H_{SW}^-)/2$ were summarized and plotted as a function of I_{DC} with the in-plane bias field $H_x = \pm 2$ kOe in Figure A-4(a). H_{eff}^z is linearly dependent on I_{DC} . The slopes of corresponding linear fittings provide the torque

efficiency $\chi = H_{eff}^z / J$ for the in-plane bias field $H_x = \pm 2$ kOe. Figure A-4(b) shows the plot of χ with respect to applied bias field H_x . χ increases quasi-linearly with H_x and saturates at around $H_x = \pm 1700$ Oe. As a result, the SHE-torque efficiency $\chi_{SHE} \approx 75.5$ Oe/ 10^{11} A·m⁻² and the effective DMI field $H_{DMI} \approx 1700$ Oe were estimated.

Figure A-4. (a) The SHE-induced effective field H_{eff}^z as a function of I_{DC} with the in-plane bias field $H_x = \pm 2$ kOe. The solid lines are the corresponding linear fits. (b) The summarized $\chi = H_{eff}^z / J$ as a function of applied in-plane bias field H_x . The SHE-torque efficiency $\chi_{SHE} \approx 75.5$ Oe/ 10^{11} A·m⁻² and the effective DMI field $H_{DMI} \approx 1700$ Oe.

A.4 Unusual magnetization switching induced by SOT

Similar to field-driven magnetization switching, SOT-induced magnetization switching was investigated by the measurements of the DC current dependence of the Hall resistance R_H with applied an in-plane bias field. During the measurements, the DC current was swept between ± 10 mA with various fixed longitudinal magnetic fields H_x . Due to the PMA in the structure, the device can be initially magnetized along $+z$ -orientation ($M_{z-initial} > 0$) or $-z$ -orientation ($M_{z-initial} < 0$) before the measurements. The DC current sweep was applied in two different ways. The first by sweeping from $+10$ mA to -10 mA, and then $+10$ mA, and the other from -10 mA to $+10$ mA, and then back to -10 mA. To gain full insight into the sweep sequence's effect on SOT-induced magnetization switching, the measurements under a fixed H_x were performed in four cases of configurations, via the combinations of the initial magnetized state ($M_{z-initial} > 0$ or $M_{z-initial} < 0$) and the DC current sweep sequence. Deterministic magnetization switching was obtained when the in-plane bias field was greater than 500 Oe in our experiments. Nevertheless, the magnetization switching exhibits distinct behaviors when an in-plane bias field of 500 Oe or greater than 1 kOe is applied.

Figure A-5 shows the SOT-induced magnetization switching with applied in-plane bias field $H_x = \pm 500$ Oe. The four measurement configurations with $H_x = +500$ Oe are shown in Figure A-5(a), A-5(c), A-5(e), and A-5(g). The corresponding results with $H_x = -500$ Oe are shown in Figure A-5(b), A-5(d), A-5(f), and A-5(h). All the obtained R_H - I_{DC} loops reveal full magnetization switching induced by SOT. Of the four measurement configurations under $H_x = +500$ Oe or $H_x = -500$ Oe, three configurations results in the same switching behavior, where the switching happens in positive current region. This Unusual magnetization switching induced by SOT can be attributed to the

field-like effective field, which shifts the magnetic loops acting as a negative H_y (see Figures A-3(c) and A-3(d)). [20] The switching process can be explained by the reversal of numbers of domains, as interpreted from Figure A-2. A different switching behavior, where the switching happens in both positive and negative current regions, is obtained one configuration. This behavior is consistent with reported results of SOT-induced magnetization switching. [12, 20, 21, 25] For $H_x = +500$ Oe, the configuration of $M_{z-initial} < 0$ and DC current sweep starting from +10 mA, gives the unique switching behavior, as shown in Figure A-5(g). In this behavior, the switching process to +z-orientation becomes sharp, like the uniform switching in Figure A-1. For $H_x = -500$ Oe, the unique switching behavior results from the configuration of $M_{z-initial} > 0$ and DC current sweeping from +10 mA to -10 mA, and then going back to +10 mA, as shown in Figure A-5(d). The results suggest that the initial magnetization state and the DC current sweep sequence also have effects on the SOT-induced magnetization switching process through modulating the mode of switching, under the in-plane bias fields of 500 Oe.

Figure A-5. The measured Hall resistance R_H as a function of DC current I_{DC} with applied in-plane bias field $H_x = +500$ Oe (a), (c), (e), and (g), and $H_x = -500$ Oe (b), (d), (f), and (h), for four types of measurement configurations, coming from the combination between the initial magnetization state ($M_{z-initial} > 0$ or $M_{z-initial} < 0$) and the DC current sweep sequence ($+10 \text{ mA} \rightarrow -10 \text{ mA} \rightarrow +10 \text{ mA}$, or $-10 \text{ mA} \rightarrow +10 \text{ mA} \rightarrow -10 \text{ mA}$).

Figure A-6. The measured Hall resistance R_H as a function of DC current I_{DC} with applied in-plane bias field $H_x = +1$ kOe (a), (c), (e), and (g), and $H_x = -1$ kOe (b), (d), (f), and (h), for four types of measurement configurations.

Figure A-7. The measured Hall resistance R_H as a function of DC current I_{DC} with applied in-plane bias field $H_x = +2 \text{ kOe}$ (a), (c), (e), and (g), and $H_x = -2 \text{ kOe}$ (b), (d), (f), and (h), for four types of measurement configurations.

When the in-plane bias field increases to 1 kOe and 2 kOe, the effects of the initial magnetization and the DC current sweeping pattern can be ignored. The experimental results show the same switching behavior loops in the four configurations with in-plane bias field of ± 1 kOe or ± 2 kOe, as the obtained R_H - I_{DC} loops are the same in the four configurations, as shown in Figure A-6 and Figure A-7, respectively.

The R_H - I_{DC} loops for in-plane bias field of $H_x = +1$ kOe and $H_x = -1$ kOe are replotted in Figure A-8(a). The positive and negative in-plane bias fields result in opposite R_H - I_{DC} loops. The switching only happens in positive current region, which is attributed to the shift of the magnetic loop by the field-like SOT. Figure A-8(b) shows the obtained R_H - I_{DC} loops for in-plane bias field of $H_x = +1$ kOe and $H_x = +2$ kOe. The critical current density maintains the same value of $\sim 10^5$ A/cm², though the in-plane bias field is increased from 1 kOe to 2 kOe. The results demonstrate that an in-plane bias field of 1 kOe is enough to overcome the DMI, which gives rise to settled mode of magnetization switching via the modulation of current. As a result, only the magnetization switching direction can be changed by the direction of in-plane bias field.

Figure A-8. (a) SOT-induced magnetization switching with applied in-plane bias field $H_x = \pm 1$ kOe. (b) SOT-induced magnetization switching with applied in-plane bias field $H_x = +1$ kOe and $H_x = +2$ kOe.

A.5 Summary

In summary, the magnetization switching induced by SOT in perpendicularly magnetized Pt/Co/Ta structure is studied. The Unusual magnetization switching behaviors, where switching only happens in positive current region, is observed and attributed to field-like SOT, which shifts the magnetic loops acting as a negative H_y . It is also found that the initial magnetization state and the DC current sweeping pattern also have effects on the SOT-induced magnetization switching process under small in-plane bias fields. When the in-plane bias field is large enough to overcome the DMI, the effects of the initial magnetized state and the DC current sweep sequence can be ignored.

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