Current-induced spin-orbit torque effective fields in multilayer structures with perpendicular magnetic anisotropy

Engel, Christian

2018

Engel, C. (2018). Current-induced spin-orbit torque effective fields in multilayer structures with perpendicular magnetic anisotropy. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/75904>

<https://doi.org/10.32657/10356/75904>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

CURRENT-INDUCED SPIN-ORBIT TORQUE
EFFECTIVE FIELDS IN MULTILAYER STRUCTURES
WITH PERPENDICULAR MAGNETIC ANISOTROPY

CHRISTIAN ENGEL

Division of Physics and Applied Physics
School of Physical and Mathematical Sciences
Nanyang Technological University

2018

CURRENT-INDUCED SPIN-ORBIT TORQUE
EFFECTIVE FIELDS IN MULTILAYER STRUCTURES
WITH PERPENDICULAR MAGNETIC ANISOTROPY

CHRISTIAN ENGEL

School of Physical and Mathematical Sciences

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

2018

ABSTRACT

Current-induced spin-orbit torque (SOT) effects are usually attributed to spin Hall effect (SHE) occurring in an adjacent nonmagnetic heavy metal layer attached to a ferromagnetic metal (FM) layer and Rashba effect at the FM interface. SOT effects currently draw much attention to the research community due to their potential of magnetization switching and magnetic domain wall (DW) driving. While being firstly experimentally observed in the early 2000's, contradicting results have been reported about the magnitude of SOT effective fields in nominal identical systems, the correlation between dampinglike and fieldlike SOT terms and even unexpected angular dependence behavior of SOT fields with respect to the magnetization direction have been reported which requires further understanding of SOT fields in lateral confined multilayer structures.

In this thesis, various properties of several multilayer structures with perpendicular magnetic anisotropy (PMA) have been investigated, notably the influence of magnetization azimuthal variation on SOT effective fields. First, the quantification of SOT effective fields using harmonic Hall voltage technique based on anomalous Hall effect (AHE) only was compared with the *in-situ* current-induced DW depinning field method of a pinned DW at the Hall cross. This allows for a direct comparison of SOT effective fields which manifests the importance of the planar Hall effect (PHE)-symmetry using the harmonic Hall voltage technique for SOT effective field investigation. Also, coercivity and anisotropy fields have been shown to decrease with increasing current in the magnetic structure which is attributed SOT effects. With the consideration of the PHE-symmetry in the harmonic Hall technique method, an analytical solution for a new measurement approach to quantify SOT effective fields as a function of the magnetization azimuthal angle has been derived and experimentally successfully tested in two inherent different sample stacks with PMA. While usually a negligible azimuthal angular dependence of SOT fields is expected, an unexpected large angular dependence has been found for a Pt/(Co/Ni)₂/Co/Ta multilayer stack structure. By exploiting angular symmetries by means of Fourier series expansion of 4th order which replicates any periodic signal due to its property of the orthogonal functionality, $-\sin 2\varphi$ and $-\cos 4\varphi$ dependencies of the SOT fields with respect to the magnetization azimuthal angle have been found. A large angular dependent field offset in the first harmonic Hall voltage has also been observed. Suggesting a unidirectional in-plane exchange bias (EB)-like field, a formula for the angular dependence of

the field offset is derived which is well fitted to the data values and confirms the unidirectional **EB** field in the Pt/(Co/Ni)₂/Co/Ta structure, which does not exhibit the usually required antiferromagnetic/**FM** layers interface. The in-plane **EB** field is attributed to the composition of the **FM**/**FM** multilayer structure with large/low magnetocrystalline anisotropy constants in combination with the amorphous Ta capping layer controlling the grain size of the polycrystalline heterostructure. The anisotropy field, H_K , also exhibits an angular dependence with spikes at azimuthal angles 45° and 225°. This is mainly attributed to the reorientation in field offset direction at these angles as well as intrinsic anisotropy transformations within the structure, as observed by the change in **DW** depinning directions and small uncertainties in the determination of the Hall resistance ratio of **PHE**/spin Hall magnetoresistance (**SMR**) to **AHE** resistances. The computation of the anisotropy and **SOT** fields detection also reveal no influence due to **EB**-like field which proposes any correlation of **SOT**, H_K , **SMR** and **EB** must be intrinsically related *via* spin-orbit coupling (**SOC**).

ACKNOWLEDGMENTS

I would like to offer my sincerest gratitude to those who have made it possible for me to complete this work. First, I want to thank Assc. Prof. Wen Siang Lew, for accepting me into his lab and allowing me to choose freely my research area. I am also grateful to the Singapore International Graduate Award (SINGA) which enabled me to pursue graduate school due to financial support.

Next, I am very grateful for the time I could spend with Dr. Sarjoosing Goolaup and also the guidance and patience he provided in training me the fundamental skills needed to elaborate research. Without his foresight views I would not be able to finish this work. Also, he was a great companion to whom I could share my thoughts. My special thanks goes to Feilong Luo for being a great companion during graduate school and for the great discussions about research which helped me in forming my own research ideas.

I would like to thank Ramu Maddu and Gerard Lim who helped me getting started in this lab and were always able to provide assistance when I faced difficulties during my studies. I had also the pleasure to work with Weiliang Gan and Waicheung Law and Farhan Nur Kholid who helped me pursuing my ideas using different equipments. I would also like to thank the whole lab members. There are many other fellow graduate students and postdocs to whom I owe a great debt for their encouragement and camaraderie throughout my time at Nanyang Technological University noteworthy Christian Zielinski, Julien Rapet, Marc Courte, Dr. Roberto Gonzalez and Ruta Vaida.

Last but not least I would also thank my wife Bernadette and my parents for their support without I wouldn't have been able to master the past years I spent pursuing my PhD studies.

CONTENTS

INTRODUCTION	xix
1 THEORY	1
1.1 Magnetic energies and fields	1
1.1.1 Exchange energy	1
1.1.2 Magnetocrystalline anisotropy energy	2
1.1.3 Zeeman energy	3
1.1.4 Demagnetizing energy	3
1.1.5 Dzyaloshinskii-Moriya energy	4
1.1.6 Micromagnetics	5
1.2 Perpendicular magnetic anisotropy	7
1.3 Magnetic domain walls	8
1.4 Spin-Orbit coupling	10
1.4.1 Rashba effect	12
1.4.2 Spin Hall effect	13
1.5 Magnetization dynamics	17
1.5.1 Landau-Lifshitz equation	17
1.5.2 Current-induced spin torques	17
1.6 Detection of magnetization manipulation	20
1.6.1 Hall effect	20
1.6.2 Anomalous Hall effect	21
1.6.3 Planar Hall effect	21
1.6.4 Spin Hall magnetoresistance	22
2 DEVICE FABRICATION AND EXPERIMENTAL SETUP	23
2.1 Device fabrication	23
2.1.1 Film sputtering	23
2.1.2 Device patterning	25
2.2 Harmonic Hall measurement setup	27
3 CONCURRENT QUANTIFICATION OF SPIN-ORBIT TORQUE EFFECTIVE FIELDS	31
3.1 Motivation	31
3.2 Experimental details	32
3.3 Effect of bias current on switching field	33
3.4 Probing of current-induced domain wall depinning field modulation	36
3.5 Hall measurements to investigate anisotropy and SOT effective fields	41
3.6 Summary	45
4 MAGNETIZATION ANGULAR DEPENDENCE OF SOT FIELDS	47

4.1	Motivation	47
4.2	Analytical derivations	48
4.2.1	Modulation of the magnetization angle by magnetic field	48
4.2.2	Harmonic Hall voltage modulation <i>via</i> current	50
4.2.3	Angular dependence of SOT effective fields	52
4.2.4	Calculation of SOT effective field errors	56
4.3	Experimental details	57
4.4	Determination of ζ ratio for the BTO sample	58
4.5	Spin-orbit torque effective fields as a function of current	59
4.6	Angular dependence of SOT effective fields in BTO sample	63
4.7	Summary	65
5	SYMMETRY CHARACTERIZATION OF ANGULAR DEPENDENT SOT FIELDS	67
5.1	Motivation	67
5.2	Experimental details	68
5.3	Fourier analysis of angular dependent SOT fields	69
5.4	Angular dependence of field offset	73
5.4.1	Large field sweeps for the Ta 1.2 nm sample	74
5.4.2	Fitting of the field offset	75
5.5	Influence of exchange bias field on SOT fields	80
5.6	Longitudinal voltage measurement to distinguish PHE and SMR	82
5.7	Discussion of the influence of SMR to SOT fields	83
5.8	Summary	84
6	CONCLUSION & OUTLOOK	87
6.1	Conclusion	87
6.2	Outlook	88
A	SUPPLEMENTARY INFORMATION FOR CHAPTER 4	91
A.1	Determination of the ζ ratio for IrMn sample	91
A.2	Angular dependence of Hall voltages for IrMn sample	92
A.3	Angular dependence of SOT effective fields for IrMn sample	93
A.4	Out-of-plane anisotropy fields for IrMn sample	94
B	SUPPLEMENTARY INFORMATION FOR CHAPTER 5	95
B.1	Current-induced temperature effects on the SOT field determination	95
B.2	Angular dependence of anisotropy field	96
B.3	Equivalence of α and β coefficients with field offset equation	97
B.4	Second harmonic Hall voltage computation with a field offset	98
B.5	Field offset for ruthenium capping sample	101

B.6	Discussion on the mismatch of φ and φ_H	102
C	EFFECT OF GEOMETRICAL MODULATION ON PMTJ MAGNETIZATION REVERSAL	105
C.1	OOMMF principles	105
C.2	Motivation	107
C.3	Simulation scheme	109
C.4	Results	110
C.5	Summary	122
	BIBLIOGRAPHY	123

LIST OF FIGURES

Figure 1	Schematic of giant magnetoresistance	xix
Figure 2	Schematic of the MRAM array and SOT-MRAM proposal	xx
Figure 3	Schematic of the Dzyaloshinskii-Moriya interaction	5
Figure 4	Schematic of magnetic energy contributions . .	6
Figure 5	Schematic of total anisotropy components . . .	8
Figure 6	Schematic of magnetic flux reduction	9
Figure 7	Schematic of domain wall energy minimization effects	9
Figure 8	Schematic of a Néel wall and a Bloch wall in a magnetic system	10
Figure 9	Schematic of spin-orbit coupling	10
Figure 10	Schematic of spin-orbit coupling in two different inertial systems	11
Figure 11	Schematic of Rashba effect	12
Figure 12	Schematic of spin Hall effect	13
Figure 13	Schematic of Mott scattering	14
Figure 14	Schematic of the intrinsic spin Hall effect in the momentum-space	15
Figure 15	Schematic of side-jump	16
Figure 16	The precession of the magnetization vector $\vec{M}$ around the effective field, with and without the effect of damping	18
Figure 17	Schematic of Hall effect	20
Figure 18	Schematic of anomalous Hall effect	21
Figure 19	Schematic of planar Hall effect	22
Figure 20	Image of <i>AJA</i> magnetron sputtering system .	24
Figure 21	Schematic of a magnetron sputtering chamber	25
Figure 22	Fabrication steps of device patterning	25
Figure 23	Image of <i>Raith e-line</i> system for EBL	26
Figure 24	Image of <i>AJA</i> ion milling system	27
Figure 25	Schematic of the harmonic Hall measurement technique	28
Figure 26	Image of the experimental setup for harmonic Hall measurement	29
Figure 27	Hysteresis loop using polar MOKE and Hall voltage technique of a Pt/(Co/Ni) ₄ /Co/IrMn heterostructure	32
Figure 28	Schematic and SEM image of the Hall structure	33
Figure 29	Differential polar MOKE images	34

Figure 30	Coercivity vs. current density plot	35
Figure 31	Domain wall depinning for both magnetization orientations at field sweeps longitudinal and transverse with respect to the wire long axis	37
Figure 32	Schematic of a Néel and Bloch domain wall with a spin current arising from the underlayer	38
Figure 33	First and second harmonic Hall resistances while depinning of a domain wall	39
Figure 34	Determination of depinning fields from Hall resistance	40
Figure 35	First and second harmonic Hall voltages as a function of the longitudinal and transverse applied fields at 10 mA bias current	42
Figure 36	Dampinglike and anisotropy field for both magnetization orientations as a function of the current in the wire	43
Figure 37	Fieldlike field using harmonic Hall voltage modulation and comparison with depinning field using PHE correction	44
Figure 38	Schematic of device structure and description of magnetization and applied field angles	48
Figure 39	Coefficients α and β for various ξ ratios	53
Figure 40	Error propagation of $\Delta(\alpha)$ for various ξ ratios through an azimuthal angle offset of $\Delta(\varphi_H) = 0.5^\circ$	57
Figure 41	PHE&SMR to AHE resistance ratio determination for BTO sample	59
Figure 42	First and second harmonic Hall voltages as a function of the longitudinal and transverse applied fields for the BTO sample.	61
Figure 43	SOT effective fields as a function of current density for BTO sample	62
Figure 44	Angular dependence of $b_{2\omega}$, b_ω , B_{φ_H} and residual of B_{φ_H} -fit for BTO sample	63
Figure 45	Angular dependence of SOT effective fields for BTO sample	64
Figure 46	Angular dependence of b_ω , $b_{2\omega}$ and B_{φ_H} for Ta 1.2 nm and Ta 2.4 nm sample	69
Figure 47	Fourier analysis of angular dependent SOT effective fields for Ta 1.2 nm and Ta 2.4 nm sample	71
Figure 48	Angular dependence of the field offset of the first harmonic Hall voltage for the Ta 1.2 nm and Ta 2.4 nm sample	74
Figure 49	Large field sweeps for every 45° steps for Ta 1.2 nm sample	75
Figure 50	Schematic of intrinsic exchange bias field	75

Figure 51	Fits to the angular dependence of field offset .	78
Figure 52	$\partial^2 V_X / \partial H^2 - \varphi_H$ plot for Ta 2.4 nm sample	82
Figure 53	Schematic drawing explaining the SMR effect .	83
Figure 54	Schematic of the proposed ferroelectric/ferromagnetic bilayer structure	89
Figure 55	ζ ratio determination for IrMn sample	91
Figure 56	Angular dependence of $b_{2\omega}$, b_ω , B_{φ_H} and the residual of the B_{φ_H} -fit for IrMn sample	92
Figure 57	Angular dependence of SOT effective fields for IrMn sample	93
Figure 58	Angular and current dependence of out-of-plane anisotropy effective fields for IrMn sample	94
Figure 59	SOT effective fields and R_ω - H loop for Ta 2.4 nm capping	95
Figure 60	Angular dependence of anisotropy field of the first harmonic Hall voltage for the Ta 1.2 nm and Ta 2.4 nm sample	97
Figure 61	Field offset plots for the Ta/Ru sample	101
Figure 62	φ - φ_H correction plots	103
Figure 63	Corrected H_K and SOT field plots as a function of φ	104
Figure 64	Schematic of the simulated MTJ stack	110
Figure 65	Relaxed out-of-plane magnetization for MTJ stack and single layer	112
Figure 66	Fast Fourier transform for the elliptical shape .	113
Figure 67	Time-dependent perpendicular magnetization dynamics of the FL layer	114
Figure 68	Magnetization dynamics for two shapes	114
Figure 69	Magnetization reversal at different time steps for circle and egg shape	116
Figure 70	Time and frequency dependence of various energy terms for the circle and egg shape	117
Figure 71	Switching time-dependence on the current density for various shapes	118
Figure 72	Switching current vs. exchange constant of the FL for the egg shape	120
Figure 73	Switching current vs. damping constant of the FL for the egg shape	121

Figure 74	Switching current vs. saturation magnetization of the FL for the egg shape	121
-----------	--	-----

LIST OF TABLES

Table 1	Parameter of the Fourier analysis for Ta 1.2 nm and Ta 2.4 nm sample	73
Table 2	Parameter of the fits from the field offset for Ta 1.2 nm and Ta 2.4 nm sample	79

ACRONYMS

AC	alternating current
AP	antiparallel
AHE	anomalous Hall effect
AFM	antiferromagnetic metal
AMR	anisotropic magnetoresistance
ANE	anomalous Nernst effect
BTO	barium titanate (BaTiO_3)
CMOS	complementary metal-oxide-semiconductor
CIP	current in the plane
CPP	current perpendicular to plane
DC	direct current
DMI	Dzyaloshinskii-Moriya interaction
DSP	digital signal processor
DW	domain wall
DWM	domain wall motion
EB	exchange bias
EBL	electron beam lithography

FE	ferroelectric insulator
FFT	fast Fourier transform
FI	ferromagnetic insulator
FL	ferromagnetic free layer
FM	ferromagnetic metal
FMR	ferromagnetic resonance
GDS	graphic database system
GMR	giant magnetoresistance
HDD	hard disk drive
HM	heavy metal
IL	insulator layer
IrMn	iridium manganese (IrMn_3)
IMA	in-plane magnetic anisotropy
IPA	isopropyl alcohol ($\text{C}_3\text{H}_8\text{O}$)
LLG	Landau-Lifshitz-Gilbert
MIBK	methyl isobutyl ketone
MOKE	magneto-optic Kerr effect
MRAM	magnetoresistive random access memory
mr-Rem	<i>micro resist (technology) Remover</i>
MTJ	magnetic tunnel junction
NM	nonmagnetic metal
OHE	ordinary Hall effect
OOMMF	object oriented micromagnetic framework
P	parallel
PHE	planar Hall effect
PL	ferromagnetic polarizer layer
PLD	pulsed laser deposition
PMA	perpendicular magnetic anisotropy
PMMA	4 % 950 k molecular weight of polymethyl methacrylate in anisole

pMTJ	perpendicular magnetic anisotropy MTJ
RF	radio frequency
SAF	synthetic antiferromagnetic layer
SHE	spin Hall effect
SMR	spin Hall magnetoresistance
SNR	signal-to-noise ratio
SOC	spin-orbit coupling
SOI	spin-orbit interaction
SOT	spin-orbit torque
SRAM	static random access memory
STT	spin-transfer torque
STT-MRAM	spin-transfer torque MRAM
TMR	tunnel magnetoresistance
TTL	transistor-transistor logic
YIG	yttrium iron garnet

INTRODUCTION

Spintronics (or spin transport electronics) is the connection between the spin degree of freedom of electrons with the transport of electrons for achieving the active transfer and manipulation of magnetic moments [166, 160, 50]. Various interpretations exist at which time actually the term 'spintronics' began to arise. Pioneering discoveries such as Mott's calculations of spin-dependent scattering of electrons on the nuclei in 1929 [109] over magnetic tunneling experiments by [Juliere](#) in 1975 [71] to the injection of magnetization into a normal metal discovered by [Johnson and Silsbee](#) in 1985 [70] are strong candidates to starting the spintronics period. The most prominent event related to spintronics was the discovery of the giant magnetoresistance ([GMR](#)) effect by Peter Grünberg [13] and Albert Fert in 1988 [6] which also provided them with the Nobel Laureate prize for physics in 2007 [50]. Others state that the industrial integration of spintronic concepts into commercial product was the utmost event which drove the new field of spintronics research to unforeseen discoveries of effects since then. As such, the integration of read/write head in hard drives ~ 1990 by *IBM* based on the anisotropic magnetoresistance ([AMR](#)) effect was the beginning of the spintronics industry thus far.

Figure 1: Schematic of giant magnetoresistance effect. A low resistance is obtained as the two ferromagnetic layers are parallel aligned while the resistance increases for an antiparallel configuration of the magnetic layers. (a) The current is applied in the layer interface plane and in (b) the current is applied perpendicular to the layer interface plane resulting in a larger magnetoresistance as compared to the in-plane applied current.

The [GMR](#) effect is ascribed to the scattering of electrons as current passes through a spin valve, giving rise to different resistance states depending on the orientation of the respective magnetization orientation, parallel (low resistance) and anti-parallel (high resistance). By

passing a current through the device, a magnetoresistance can be read out which informs us of the relative configuration of magnetizations of both FM layers in either parallel or antiparallel state. To read the information, either current in the plane (CIP) [6] or current perpendicular to plane (CPP) of the device is applied [89, 64, 46], as shown in Fig. 1. The GMR effect replaced the AMR effect-based read heads

Figure 2: Schematic of the MRAM array with Bit and Word lines (a) and the proposed SOT-MTJ device for SOT-MRAM application.

in hard disk drive (HDD) read head's ~ 1998 [36, 154]. Soon after, the GMR was replaced by the tunnel magnetoresistance (TMR) effect where the nonmagnetic metal (NM) separation layer was substituted by an ultrathin insulator layer (IL) [106, 108, 68]. This FM/IL/FM trilayer structure became known as magnetic tunnel junction (MTJ), where large magnetoresistances are used as base for the magnetoresistive random access memory (MRAM) where the bit '0' or '1' is stored by the respective magnetic layer configuration being in parallel or antiparallel configuration, as shown in Fig. 2 (a).

Berger and Slonczewski postulated that a spin-polarized current should be able to change the magnetic state of a ferromagnet via spin-transfer torque (STT) mechanism [9, 142]. As such, the magnetic state can be 'written' by passing a large current through the MTJ which became known as spin-transfer torque MRAM (STT-MRAM) in recent years [47]. Due to scalability limitation of in-plane magnetic systems, the focus in recent years shifted towards PMA systems which can be further minimized due to cancellation of the demagnetizing field and even larger TMRs as compared to in-plane magnetic anisotropy (IMA) systems are observed [90, 24, 3]. With the search for new, low power magnetization switching, Liu et al. [93] proposed a 3-terminal MTJ device based on SOT-switching, as depicted in Fig. 2 (b).

SOT is believed to arise from Rashba effect induced due to an emerging electric field at the FM interface and SHE in a NM layer. The beginning of SHE was the prediction of the extrinsic SHE from Dyakonov and Perel in 1971 [40] who described the phenomenological effect using Mott scattering as a model. The SHE was firstly named and rediscovered by Hirsch in 1999 [63]. Thereupon, Murakami et al. and Sinova et al.

[110, 140] independently described an intrinsic contribution of the SHE which was yet to be experimentally discovered. In 2004, Kato et al. [75] optically observed the extrinsic SHE and Wunderlich et al. [168] observed the intrinsic SHE. Theoretical calculations from Obata and Tataru and Manchon and Zhang in 2008 [117, 97] for SOT in FM layers led to the observation of the fieldlike term in FM layers shortly after by Miron et al. [104, 105]. Chernyshov et al. in 2009 [31] showed in zinc blende structure electrically the manipulation of the magnetization by means of spin-orbit magnetic field. Since then, various methods to probe spin-orbit fields have emerged such as alternating current (AC) Hall voltage modulation [130, 76, 53], spin-torque ferromagnetic resonance (FMR) [91, 49], magneto-optic Kerr effect (MOKE) [48] and domain wall motion (DWM) [41, 56, 135].

Yet results using different techniques are contradicting each other [62, 130, 92, 76, 53, 121, 61, 48, 131, 137]. Hayashi et al. later in 2014 expanded the AC harmonic Hall voltage technique using both the AHE and the PHE as detection signals in PMA structures [61].

Magnetization switching *via* a phenomenon which is not totally understood leaves various difficulties in implementation into devices. Especially new material systems promise a new path towards field-free magnetization switching for the integration into future magnetic memory devices. Early results on magnetization switching by SOT have been realized in both in-plane and out-of-plane magnetic anisotropy systems using an in-plane bias field canceling the dipole field and creating an asymmetry to the switching field [93, 124, 34]. However, a bias field was required, that hinders the technological integration into devices. The need for field-free magnetization reversal led to the implementation of a lateral structure asymmetry to creating such an in-plane bias field intrinsically [174]. Recent studies coinciding with this thesis have focused on the integration of an antiferromagnetic metal (AFM) layer to induce tilting in the FM layer, akin to the application of an external field [52, 85, 157]. Yet this design architecture still faces challenges for reliable fabrication. This calls for further understanding of SOTs and SOT effective fields.

Therefore, further understanding of SOT effects is required which I try to focus on in this thesis.

The focus of this thesis lies in the fundamental investigation SOT effective fields in various multilayer structure.

The thesis is arranged as follows:

- Chapter 1** provides the basic theory to understand this thesis.
- Chapter 2** explains the sample fabrication and the experimental setup for our measurement scheme of the mostly used harmonic Hall voltage scheme.
- Chapter 3** presents the introduction of SOT measurement using harmonic Hall technique and compares the results with current-induced DWM.
- Chapter 4** describes the analytical calculation for SOT angular dependence measurement on the magnetization and first experimental verification.
- Chapter 5** contains a study on the angular dependence of SOT fields and an analytical model for describing a newly discovered in-plane EB-like field in PMA structures.
- Chapter 6** provides the conclusion from this thesis as well as an overview for future works.

THEORY

In this chapter, I provide the theoretical background which is useful to understand this thesis. Starting from the total magnetic energy equation for a magnetic system, the energy minimization for a dynamic magnetic system is elucidated. Thereupon, the SOC phenomenon is introduced and finally the detection through magnetization manipulation is presented.

1.1 MAGNETIC ENERGIES AND FIELDS

The effective field in a magnetic material is usually described by the total magnetic energy of the magnetic material with respect to the volume or rather by the energy density $f = \frac{\partial E}{\partial V}$. The effective field in a magnetic system then can be computed as

$$\vec{H}_{Eff} = -\frac{1}{\mu_0} \frac{\partial f}{\partial \vec{M}}. \quad (1)$$

μ_0 is the permeability of free space which is commonly known as $\mu_0 = 4\pi \times 10^{-7}$ H/m. In general, the total magnetic energy is described by

$$E_{Tot} = E_Z + E_{Ex} + E_{Dem} + E_{An} + E_{DMI}, \quad (2)$$

where E_Z is the Zeeman energy, E_{Ex} is the exchange energy, E_{Dem} is the demagnetizing energy, E_{An} is the magnetocrystalline anisotropy energy and E_{DMI} is the Dzyaloshinskii-Moriya interaction (DMI) energy. Further magnetic energy terms such as the magnetoelastic energy are not considered in this thesis. The specific energy terms are described in detail in the following.

1.1.1 Exchange energy

The exchange energy has its origin in quantum mechanics. Considering two electrons with spins $\vec{S}_1$ and $\vec{S}_2$, the spin-spin coupling of identical particles is described by the exchange interaction. Depending on the spatial state, the electrons must adopt either an antisymmetric singlet state for a symmetric spatial state or adopt a symmetric triplet state for an antisymmetric spatial state [14]. This is described in the Heisenberg model of two spins as given by the Hamiltonian [14]

$$\mathcal{H} = -2J\vec{S}_1 \bullet \vec{S}_2. \quad (3)$$

J is the exchange coupling constant or exchange integral and $\vec{S}_1$ and $\vec{S}_2$ are the spins of the two electrons at positions $\vec{r}_a$ and $\vec{r}_b$. The exchange coupling constant is given by

$$J = \frac{1}{2} (E_{\text{Singlet}} - E_{\text{Triplet}}), \quad (4)$$

where E_{Singlet} is the energy of the singlet state and E_{Triplet} is the energy of the triplet state. A positive exchange coupling constant ($J > 0$) indicates a ferromagnetic interaction (neighboring spins favoring $\uparrow\uparrow$ alignment) whereas a negative exchange coupling constant ($J < 0$) indicates an antiferromagnetic interaction (neighboring spins favoring $\uparrow\downarrow$ alignment). In general, it is sufficient to consider nearest neighbor electron spins as the interaction is short ranged. However, with the assumption the angle, γ , between the spins $\vec{S}_1$ and $\vec{S}_2$ is small, the exchange energy, E_{Ex} , is given by [66]

$$E_{\text{Ex}} = \frac{A_{\text{Ex}}}{M_S^2} \int |\nabla \vec{M}|^2 dV, \quad (5)$$

where A_{Ex} is the exchange stiffness constant, which is directly proportional to the exchange coupling constant, J . In most cases, the magnetic vectors of atoms can be approximated as perfectly parallel aligned which leads to a constant exchange energy in the magnetic system.

1.1.2 Magnetocrystalline anisotropy energy

The magnetocrystalline anisotropy energy finds its origin in the spin-orbit interaction (SOI) of electrons. The orientation of the electron orbitals is associated with the crystallographic structure of the magnetic system and interact with the electron spins along these crystallographic axes. As a result, the electron spins prefer a parallel alignment with respect to the distinct crystallographic axes, also known as easy axes [141, 14]. In other words, there exist orientations in a single or polycrystalline magnetic material along which the magnetization is easier (easy axis) or harder (hard axis) to align. The magnetocrystalline anisotropy is usually described in terms of the anisotropy energy density and is given by [1]

$$E_{\text{An}} = \int f_{\text{An}} dV, \quad (6)$$

where f_{An} is the anisotropy energy density. For a cubic crystal the energy density can be expressed by a power series expansion leading to a basic formula [66]

$$f_{\text{An}} = K_1(m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2) + K_2 m_1^2 m_2^2 m_3^2, \quad (7)$$

where m_i are the components of the magnetization aligned along cubic axes $i = 1, 2$ and 3 . K_1 and K_2 are material constants. K_1 is usually in the order of $\pm 10^4$ J/m³ and K_2 is usually small as compared to K_1 and therefore neglected for most systems.

The magnetocrystalline anisotropy is typically small in comparison with the exchange energy. For uniaxial anisotropy, the anisotropy energy density second order is usually described by [141]

$$f_{An} = K_1 \sin^2 \theta, \quad (8)$$

where θ denotes the elevation angle of the magnetization vector from the plane. However, the magnetocrystalline anisotropy has a dominant role in magnetic materials with PMA which mostly arises from the Co/Pt interface in ultrathin Co-based magnetic layers.

1.1.3 Zeeman energy

The Zeeman energy exists when an external magnetic field, $\vec{H}$, is applied to a magnetic system. The magnitude of the energy depends on the angle, γ , between the magnetization of the system, $\vec{M}$, and the external field, $\vec{H}$. The Zeeman energy is expressed by the volume integral of the magnetization with respect to the applied field [66]

$$E_Z = -\mu_0 \int \vec{H}_{Ext} \bullet \vec{M} dV. \quad (9)$$

1.1.4 Demagnetizing energy

The demagnetizing field arises due to uncompensated magnetic moments, which occur at the surface of magnetic elements or due to spatial changes of the magnetization. To minimize the magnetic field lines (or magnetic flux at the surfaces) from the element and therefore the energy, the magnetization tries to align parallel to boundaries of the element. Hence, the demagnetizing field depends strongly on the shape of the element. From the Maxwell equation

$$\nabla \bullet \vec{B} = 0 \quad (10)$$

and the formula for the magnetic field

$$\vec{B} = \mu_0 (\vec{H}_{Dem} + \vec{M}), \quad (11)$$

where $\vec{H}_{Dem}$ is the demagnetizing field, we can derive the following relation for the volume charges

$$\nabla \bullet \vec{H}_{Dem} = -\nabla \bullet \vec{M}. \quad (12)$$

From this expression, the demagnetizing energy can be calculated as [1]

$$E_{Dem} = -\frac{\mu_0}{2} \int \vec{H}_{Dem} \bullet \vec{M} dV. \quad (13)$$

This demagnetizing energy arises from the magnetic field generated by the system even in the absence of an external field, $\vec{H}_{Ext}$. For the limiting case of an ellipsoidal magnetic structure, the demagnetizing field can be relatively simple approximated by [14]

$$\vec{H}_{Dem} = N\vec{M}. \quad (14)$$

where N is the demagnetizing tensor [122]. In its simplest form the demagnetizing tensor can be diagonalized as

$$N = \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}. \quad (15)$$

The demagnetizing tensor components fulfill the following relationship:

$$N_x + N_y + N_z = 1. \quad (16)$$

For a sphere with equal length of the magnetic structure in every axis direction, $N_x = N_y = N_z = 1/3$. For an ultrathin magnetic plate with surface normal pointing in z-direction, $N_x = N_y = 0$, $N_z = 1$. The demagnetizing tensor components are therefore related to the length of the magnetic structure body in every direction. With N_x and N_y being 0, the demagnetizing field is directed in the z-direction trying to align the magnetization in the x-y plane.

1.1.5 Dzyaloshinskii-Moriya energy

The DMI is also known as antisymmetric exchange interaction. In the presence of SOC, two magnetic ions minimize their global magnetic energy by canting their magnetic moments which is known as DMI. The Hamiltonian of this interaction between two magnetic moments can be written as [14]

$$\mathcal{H}_{DMI} = -\vec{D} \bullet (\vec{S}_1 \times \vec{S}_2). \quad (17)$$

The vector $\vec{D}$ is the so-called DMI exchange constant which represents the strength of the DMI. Neighboring spins $\vec{S}_1$ and $\vec{S}_2$ tend to align in a 90° angle within a plane which is orthogonal to the vector $\vec{D}$, as seen in Fig. 3 (a). This ensures the energy is minimized at negative values. As this energy stands in competition to the other energy terms described earlier, the spins usually slightly cant away from one another. The energy term is commonly seen in antiferromagnetic compounds such as MnCoO_3 and CoCO_3 which results in a small magnetic angle tilt and therefore a weak ferromagnetic component [14].

Figure 3: Schematic of the bulk Dzyaloshinskii-Moriya interaction (a) and the interfacial Dzyaloshinskii-Moriya interaction (b).

In recent years, the interfacial **DMI** has attracted a lot of attention as the interaction naturally appears in heavy metal (**HM**)/**FM** multilayer stacks which are investigated for **SOT** examination [37, 95, 125, 165]. Here, the canting of spins of the **FM** is caused by the **SOI** from the **HM** which can be seen in Fig. 3 (b). The **DMI** energy is then given by [51]

$$E_{DMI} = \int f_{DMI} dV, \quad (18)$$

with f_{DMI} being

$$f_{DMI} = D \left(m_z \frac{\partial m_x}{\partial x} - m_x \frac{\partial m_z}{\partial x} + m_z \frac{\partial m_y}{\partial y} - m_y \frac{\partial m_z}{\partial y} \right). \quad (19)$$

D is the area unit energy density associated with the vector $\vec{D}$ usually by the proportional factor $1/a_0 t$. a_0 is the atomic lattice constant and t is the film thickness of the ferromagnetic layer. D is usually given in units of mJ/m^2 .

1.1.6 Micromagnetics

The total free energy is the sum of magnetization-dependent energy contributions as given by Eq. (2). The magnetization state in a magnetic system is determined by minimizing the total free energy. The individual energy terms can be illustrated as shown in Figure 4 which represents the preferential magnetization alignment for each component.

Figure 4: Schematic of magnetic energy contributions and how they affect the effective magnetization.

With a defined uniaxial external magnetic field and uniaxial anisotropy field, the magnetization configuration can be easily approximated for a ferromagnetic system (Stoner-Wohlfart-model [146]). For a more complex system with inhomogeneous magnetization, a way to approximate the configuration with the following variational principle is given by

$$\delta E_{Tot} = 0. \quad (20)$$

Brown derived two boundary conditions for the magnetic system as [20]

$$\vec{M} \times \vec{H}_{Eff} = \vec{0}, \quad (21)$$

$$\vec{M} \times \partial_{\vec{r}} \vec{M} = \vec{0}. \quad (22)$$

Eq. (21) states that the magnetization for a static equilibrium orientation is collinear with the effective field, $\vec{H}_{Eff}$. Eq. (22) describes the alignment of the magnetization along the surface of the magnetic structure. Taking the conditions into account, the effective field $\vec{H}_{Eff}$ using Eq. (1) can be derived as

$$\vec{H}_{Eff} = \vec{H}_{Ext} + \vec{H}_{Dem} + \vec{H}_{DMI} + \frac{2A_{Exch}}{M_S^2} \Delta \vec{M} - \frac{1}{\mu_0} \partial_{\vec{M}} f_{An}. \quad (23)$$

Here, the magnetization vector, $\vec{M}$, is treated as the only independent variable.

1.2 PERPENDICULAR MAGNETIC ANISOTROPY

One of the first observations of PMA dates back to 1985 by [Carcia et al.\[23\]](#). Due to the demagnetizing energy contribution in thin films, the magnetization favors an alignment in the plane rather than turning out of the plane. This alignment of magnetic moments reduces the demagnetizing field in the magnetic body which is attributed to a reduction in magnetic flux, as shown in Fig. 5 (a). The top image depicts an out-of-plane magnetization where the intensity of the stray field outside the magnetic body is characterized by the number of magnetic moments pointing towards the surface. As more magnetic moments in the top image configuration point towards the surface as in the bottom image, more stray field is produced in the top image which is energetically not favorable. In the rare case of an ultrathin magnetic layer, the magnetic moments can turn out of the plane due to an emerging energy contribution to magnetic moments at the surface. This so-called surface anisotropy is caused by SOC at the surface where neighboring atoms with large SOC induce an out-of-plane magnetization configuration to magnetic moments at the surface [35, 164, 156, 111]. As this interaction is generally limited to neighboring atoms, the strength decreases significantly with distance which leads to the following approximation of the total anisotropy, K , as [141]

$$K = \frac{K_S}{t} - K_0, \quad (24)$$

where K_S is the surface anisotropy, t is the thickness of the magnetic film and $K_0 = K_1 - 4\pi M_S$ with K_1 the magnetocrystalline anisotropy and the shape anisotropy $-4\pi M_S$ for a thin film. K_S is generally positive. A positive K anisotropy favors an out-of-plane magnetization whereas a negative K anisotropy will align the magnetization in-plane, as shown in Fig. 5 (b).

Figure 5: (a) Schematic of magnetic body with perpendicular magnetic anisotropy (top) and in-plane magnetic anisotropy (bottom). The representative stray field (magnetic flux) is indicated in dashed lines. (b) Plot of magnetic anisotropy behavior for $K > 0$ (PMA) and for magnetic anisotropy $K < 0$ (IMA) as a function of the thickness t of the ferromagnetic layer.

1.3 MAGNETIC DOMAIN WALLS

The magnetization in a magnetic system is usually clustered by magnetic areas (domains) of collinear magnetic moments which are also called Weiss domains [78]. The magnetization in a magnetic system is usually dominated by the exchange energy which aligns the magnetic moments parallel, as shown in Fig. 6 (a). However, this setup is not always energetically favorable as for instance magnetic flux is generated at some edges. The magnetic flux is reduced by introducing two domains with opposite aligned magnetic moments separated by a sharp boundary, as shown in Fig. 6 (b). The magnetic flux can be further reduced by aligning all magnetic moments parallel to the structural edges, as shown in Fig. 6 (c). The boundaries with sharp transitions of the magnetic domains are the so-called DWs. The formation of domains occurs due to the minimization of the total free energy, E_{Tot} , in the magnetic element, in particular to reduce the demagnetizing and anisotropy field energy.

The DW can be classified by its energy per unit area and the DW width. The DW width is determined by the competition of the exchange energy and the anisotropy energy in the system, as seen in Fig. 7. In Fig. 7 (a) the anisotropy energy is minimized which results in a small DW width. The magnetic moments are mostly parallel aligned along the magnetic easy axis. In Fig. 7 (b) the exchange energy is minimized which results in a nearly parallel alignment of neighboring magnetic moments.

There exist mainly two easy types of DWs in such a bulk system where the magnetization depends on the position perpendicular to

Figure 6: Schematic of the magnetic flux reduction. (a) depicts a system with no domain walls and large area with magnetic field lines. (b) shows a reduction of the area with magnetic field lines by introducing a domain wall. (c) exhibits no magnetic flux by introducing multiple domain walls.

Figure 7: Schematic of domain wall energy minimization effects. (a) minimizes the anisotropy energy where the magnetic moments are mostly parallel aligned along the magnetic easy axis. (b) shows the minimization effect due to the exchange energy where neighboring moments are tried to be parallel aligned.

the wall only, as shown in Fig. 8: Néel walls and Bloch walls. Néel walls have spin components which rotate within the plane of the DW, whereas Bloch walls exhibit a rotation the magnetization through the plane of the DW, as shown in 8. The energy density of the Bloch DW can be approximated with respect to the exchange and anisotropy energy to [66]

$$\sigma_B \approx 4\sqrt{A \cdot K} \quad (25)$$

where A is the exchange stiffness constant and K the magnetocrystalline anisotropy constant as described in section 1.1. The wall thickness of a Bloch wall is given by [66]

$$\delta_B \approx 2\sqrt{\frac{A}{K}}. \quad (26)$$

In the case of a Néel wall within a magnetic system with a film thickness t much smaller than the DW width δ_N , the energy density and wall width are in the same range as of the Bloch wall. Therefore for ultrathin magnetic layers, Néel and Bloch DWs can be favored.

Figure 8: Schematic of (a) a Bloch wall and (b) a Néel wall in a ferromagnetic element.

It should be noted that the DMI can play an important role when a DW is present in the system due to the canting of neighboring spins.

1.4 SPIN-ORBIT COUPLING

SOC is a small correction term to the leading electrostatic energy term arising in the relativistic expansion of the Dirac equation [14]. The phenomenon is commonly described by an electron with spin momentum $\vec{s}$ orbiting around a nucleus. This closed loop of the electron causes the orbital momentum $\vec{l}$, which then couples with the spin momentum $\vec{s}$, as seen in Fig. 9 (a). However, SOC is also found in systems where any type of potential gradient or $\vec{E}$ -field gives rise to SOC with the electron spin, as shown in Fig. 9 (b). Here, the emerging $\vec{B}$ -field couples with the electron spin momentum $\vec{s}$.

Figure 9: Schematic of spin-orbit coupling. (a) ls-coupling of the spin momentum of the electron and the orbital momentum due to electron orbiting around a nucleus. (b) Bs-coupling where the $\vec{B}$ -field is generated by any $\vec{E}$ -field acting on a moving electron.

This phenomenon can be understood considering two inertial systems (a) and (b), as shown in Fig. 10. In general, the electric and magnetic fields are given by the Lorentz transformations where the two systems are moving with velocity $\vec{v}$ towards each other. The Lorentz transformations of the electric and magnetic fields parallel ($\parallel$) and transverse ($\perp$) to the constant velocity $\vec{v}$ are written as

$$\vec{E}_{\parallel}^{(b)} = \vec{E}_{\parallel}^{(a)}, \quad (27)$$

$$\vec{B}_{\parallel}^{(b)} = \vec{B}_{\parallel}^{(a)}, \quad (28)$$

$$\vec{E}_{\perp}^{(b)} = \gamma(\vec{E}_{\perp}^{(a)} + \vec{v} \times \vec{B}^{(a)}), \quad (29)$$

$$\vec{B}_{\perp}^{(b)} = \gamma(\vec{B}_{\perp}^{(a)} - \frac{1}{c^2} \vec{v} \times \vec{E}^{(a)}). \quad (30)$$

$\gamma = 1/\sqrt{1 - v^2/c^2}$ is the Lorentz factor with c the speed of light in vacuum. Using Eq. (30) ($v \ll c$), the emerging $\vec{B}$ -field can now be written as shown in Fig. 10 (b) as

$$\vec{B}^{(b)}(\vec{v}) = \frac{1}{2c^2} \vec{E}^{(a)} \times \vec{v}. \quad (31)$$

It should be noted that the $1/2$ factor is the so-called relativistic Thomas factor or Thomas half which appears due to the non-inertial frame [14]. For larger velocities, the factor follows the expression $\gamma^2/(\gamma + 1)$. The Hamiltonian for the Zeeman energy due to the SOC-field is then given by [98]

$$\mathcal{H}_{SOC} = \frac{\mu_B}{2c^2} \vec{\sigma} \cdot (\vec{E} \times \vec{v}) = \mu_B \vec{\sigma} \cdot \vec{B}, \quad (32)$$

where $\vec{\sigma}$ is the vector of the Pauli matrices.

Figure 10: Schematic of spin-orbit coupling in different inertial systems. (a) The electron is moving in a laboratory frame with a fixed $\vec{E}$ -field. (b) In the electron frame, the $\vec{E}$ -field is moving towards the electron causing a $\vec{B}$ -field.

The SOC is usually divided into two terms in a crystal system. One term is the symmetry independent SOC such as SHE. SHE exists in all types of crystals. The second term is symmetry dependent in crystals without inversion symmetry such as Dresselhaus (bulk) and Rashba (interface/surface) effect.

SOC manifests itself in various kinds of effects such as magnetocrystalline anisotropy, DMI, magnetic damping, AMR, AHE, SHE, Rashba effect and Dresselhaus effect. In this section, the SHE and the Rashba effect are discussed in more detail as they are believed to play the major contributions to the SOT effective field observations.

1.4.1 Rashba effect

The Rashba effect is commonly introduced as an interface effect. The effect arises at the interface of two crystals with crystal potential V_1 and V_2 , as seen in Fig. 11. As the crystal symmetry is broken, an electric field between the two crystals compensates the potential gradient within a screening length of typically a few nanometers [80, 169]. A conduction electron with velocity $\vec{v}$ experiences this electric field, as depicted in Fig. 11. With the velocity in x-direction and the electric field pointing along the interface normal in z-direction, the Rashba Hamiltonian can be written as [140]

$$\mathcal{H}_R = \frac{\alpha_R m}{\hbar} \vec{\sigma} \bullet (\vec{z} \times \vec{v}), \quad (33)$$

where α_R is the Rashba parameter. In the simplistic model as described in the previous section, the Rashba parameter equals to $\alpha_R = g\mu_B E/2mc^2$ with g being the g-factor. However in realistic systems, the Rashba parameter has been measured to be two orders of magnitude larger. This is ascribed to the distortion of the electron wave function near the nuclei due to the lack of inversion symmetry at the interface [98]. It should be noted that the potential gradient

Figure 11: Schematic of Rashba effect. At the interface between two crystals with different potentials V_1 and V_2 , a potential gradient emerges. An electron with velocity v experiencing the potential gradient causes an emerging $\vec{B}$ -field.

depends strongly on the band structure of the interfacial atoms which might induce a non-uniformity of the Rashba magnetic field.

1.4.2 Spin Hall effect

The SHE described by Dyakonov and Perel in 1971 [40] is based on the extrinsic Mott scattering (Skew scattering in materials) which is still the most prominent approach for SHE. In a NM with large SOC, unpolarized electrons experience a spin-dependent velocity towards the edges, as shown in Fig. 12 (a). A transverse spin current with

Figure 12: Schematic of spin Hall effect. (a) Electron entering a conductor with large spin-orbit coupling experience a spin-dependent transverse motion. (b) Plot of spin accumulation in z -direction with λ being the spin diffusion length.

respect to the charge current with zero net charge current contribution takes place. This phenomenon causes spin accumulations at the edges, as shown in Fig. 12 (b). In case of a material adjacent to the conducting material with large SOC, the spin-polarized electrons can diffuse into the adjacent material causing a spin accumulation near this interface. As SHE consists of various effects, we explain in the following three main effects causing SHE namely Mott scattering, anomalous velocity and side-jump.

Mott scattering

The Mott scattering (Skew scattering describes the effect within a material) describes the elastic scattering event of a dot-like Fermion (spin $1/2$ particle) such as an electron at a static dot-like charge particle without spin. The Mott scattering is visualized in Fig. 13. Within the electron shell, the electric field from the nucleus is predominant. An incoming electron will experience an emerging $\vec{B}$ -field as described by Eq. (31) which is equivalent to an Oersted field. Due to the radial electric field, the magnitude of the $\vec{E}$ -field from the nucleus and therefore for the $\vec{B}$ -field decreases with increasing distance from the nucleus, as shown in Fig. 13. The gradient of the magnetic field gives

Figure 13: Schematic of Mott scattering. An electron with velocity experiences spin-dependent deviation along the emerging $\vec{B}$ -field gradient.

rise to an additional spin-dependent force to the dominating Coulomb force acting on the incoming electron. The additional SOC force can be written as

$$\vec{F} = \nabla (\vec{\mu} \cdot \vec{B}). \quad (34)$$

$\vec{\mu}$ is the magnetic moment of an electron which is given by $\vec{\mu} = -\frac{eg}{2m}\vec{s}$. $-e$ is the electron charge, m is the electron mass and g is the g-factor as a result of the Dirac equation. The force can be rewritten as

$$\vec{F} = (\vec{\mu} \cdot \nabla) \vec{B} + (\vec{B} \cdot \nabla) \vec{\mu} + \vec{\mu} \times (\nabla \times \vec{B}) + \vec{B} \times (\nabla \times \vec{\mu}). \quad (35)$$

Considering two electrons of spin up ($+s_z$) and spin down ($-s_z$) with identical trajectory towards the electron shell with velocity v_x , as seen in Fig. 13, Eq. (35) reduces to

$$\vec{F} = \vec{\mu} \times (\nabla \times \vec{B}) = \pm \mu_z \frac{\partial B_z}{\partial y} \hat{e}_y. \quad (36)$$

With electrons of opposite spin, the force acts in opposite directions which is illustrated in the small deviation of the electron paths in Fig. 13. The Mott scattering is usually characterized by the asymmetry of the spin-polarized electrons moving in opposite directions which is closely related to the spin-polarization. The asymmetry is given by

$$A_{\uparrow} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = SP_{\uparrow}, \quad (37)$$

where N is the number of electrons with respective spin orientation, S is the sensitivity or Sherman factor and P is the spin polarization. The Mott scattering has been found very important for the detection of spins (spin detector) or even gives rise to the information of the shape of a nucleus.

Anomalous velocity

The idea of the anomalous velocity was firstly introduced by [Karplus and Luttinger](#) [73] in 1954 based on the theory which encounters for the equation of motion of electrons. [Smit](#) [143, 144] in 1955 and 1958 explained the anomalous velocity based on wave packets formed from Bloch band states and finally [Berry](#) [11] in 1984 introduced the geometrical phase, which is still the most common theory till date. The anomalous velocity is also called 'intrinsic deflection' as the anomalous velocity is independent of the impurity density and just depends on the electronic band structure of periodic Bloch states [110, 140]. The anomalous velocity is usually given by

$$\vec{v} = e\vec{E} \times \vec{\Omega}, \quad (38)$$

where $\vec{\Omega}$ is known as Berry curvature. The Berry curvature can be seen as an effective magnetic field in the momentum-space of the Rashba spin-split band structure. [Sinova et al.](#) [140] showed that the anomalous velocity can be understood from the spin carrier in an applied electric field with additional momentum, Δp_x , as shown in Fig. 14.

Figure 14: Schematic of the intrinsic spin Hall effect. The Fermi-surface in an effective $\vec{E}$ -field experience a torque which tilts the spin out-of-plane with opposite directions for momenta pointing towards opposite y-direction.

The steadily generated $\vec{B}_y$ -field causes the spins to precess. Assuming low damping which will be introduced in section 1.5.1, the emerging out-of-plane spin component is given by [82]

$$s_z \approx \frac{s\hbar^2}{2p^2} e E_x \sin \delta_{\vec{E}-\vec{p}}, \quad (39)$$

where $\delta_{\vec{E}-\vec{p}}$ is the angle between $\vec{E}$ -field and the carrier momentum $\vec{p}$. The sign of the out-of-plane spin, s_z , depends on the direction of the momentum transverse to the electric field in y-direction, as shown in Fig. 14. This gives rise to an additional velocity in y-direction which is independent of impurities.

Side-jump

The side-jump introduced by Berger [7] describes an extrinsic effect which produces a so-called side-jump off an impurity. The side-jump is an extrinsic effect arising from scattering against impurities. In spite of this extrinsic origin, side-jump is independent on the impurity concentration and therefore gives a contribution that acts as an intrinsic Hall contribution. A free electron described as a wave packet with constant velocity is getting deflected by the impurity. This side-jump is in the order of less than 1 Å. However, the side-jump effect is described to be spin-dependent which deflects the wave packet in opposite directions for opposite spins. After leaving the impurity the constant velocity with identical direction is recovered, as shown in Fig. 15. During the

Figure 15: Schematic of side-jump where a wave packet with velocity $\vec{v}$ is getting displaced by Δy during the perturbation of the impurity.

perturbation in the impurity field, the electrons are changing the band which creates the anomalous velocity.

1.5 MAGNETIZATION DYNAMICS

In this section, the theoretical description of externally applied magnetic field or current-induced magnetization dynamics is explained.

1.5.1 Landau-Lifshitz equation

The first mathematical description of the dynamics of the magnetization was derived by [Landau and Lifshitz](#) in 1935 [84]:

$$\frac{d\vec{M}}{dt} = -\gamma(\vec{M} \times \vec{H}_{Eff}). \quad (40)$$

The gyromagnetic ratio, γ , is given by $\gamma = \frac{g\mu_0\mu_B}{\hbar}$. Equation (40) implies a precession of the magnetization vector $\vec{M}$ around the effective field $\vec{H}_{Eff}$. The angle θ between the magnetization vector and the effective field direction does not change during the precessional motion. Thus, to obtain the equilibrium state where the magnetization, $\vec{M}$, and the effective field, $\vec{H}_{Eff}$, are aligned parallel, a second torque was added to this equation by [Landau and Lifshitz](#) which describes the damping of the precession, as shown in Figure 16. This is the so-called original Landau-Lifshitz equation [84]

$$\frac{d\vec{M}}{dt} = -\gamma_{LL}(\vec{M} \times \vec{H}_{Eff}) - \underbrace{\frac{\alpha_{LL}}{M_S} \vec{M} \times (\vec{M} \times \vec{H}_{Eff})}_{\text{Damping}}. \quad (41)$$

The damping constant, α_{LL} , has to be determined experimentally. The damping term can be thought of as a torque $\vec{T}_D$ which pushes the magnetization towards the effective field, until the directions are aligned parallel in the static solution. Gilbert introduced an alternative damping term which can be added to the Landau-Lifshitz equation (41) [84]:

$$\frac{d\vec{M}}{dt} = -\gamma_G(\vec{M} \times \vec{H}_{Eff}) + \underbrace{\frac{\alpha_G}{M_S} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right)}_{\text{Damping}}. \quad (42)$$

This form of the equation is called the Gilbert equation or Landau-Lifshitz-Gilbert (LLG). By comparing the coefficients of these two equations we can obtain the following relations [66]:

$$\gamma_{LL} = \frac{\gamma_G}{(1 + \alpha_G^2)}, \quad \alpha_{LL} = \frac{\alpha_G \gamma_G}{(1 + \alpha_G^2)}. \quad (43)$$

1.5.2 Current-induced spin torques

When a current passes through a magnetic material, the current will also influence the magnetization dynamics. As predicted by [Berger](#)

Figure 16: (a) The precession of the magnetization vector $\vec{M}$ around the effective field. (b) The precession with the additional damping torque $\vec{T}_D$ towards the effective field.

[8], due to the s-d exchange between the spin-polarized conduction electrons and the DW, there is a torque on the conduction electrons as they traverse the boundary. Reciprocally, there is a torque back on the magnetization which can cause magnetization switching, precession or DWM. This is known as STT. This was initially incorporated into the LLG equation by Slonczewski [142]. Since then, a variety of formalisms have emerged which include multiple terms for the STT. Currently, two terms considered for STT are customary as discussed below.

Adiabatic Spin-Transfer Torque

The adiabatic STT occurs if a current is injected into a magnetic structure. The spin-polarized charge current travels through DWs. The spin orientation of the conduction electrons changes to match the local direction of the magnetization configuration. An adiabatic STT is the gradual change of the electron spins towards the magnetization configuration while the electrons are traveling. The rotational movement of the angular momentum of the electrons is expressed by [150]:

$$\left(\frac{\partial \vec{M}}{\partial t}\right)_{Adiabatic}^{STT} = -(\vec{u} \cdot \nabla) \vec{M}, \quad (44)$$

with $\vec{u}$ as the effective velocity [151]

$$\vec{u} = \frac{gP\mu_B}{2eM_S} \vec{j}. \quad (45)$$

P is the spin polarization of the magnetic element and $\vec{j}$ is the current density.

Non-Adiabatic Spin-Transfer Torque

The non-adiabatic **STT** is a result of the non-adiabaticity of the spins of the electrons in tracking a change of the magnetization. A torque is exerted on the local magnetization due to the misalignment of the electron spin and the local magnetization. The non-adiabatic **STT** is given by [177]

$$\left(\frac{\partial \vec{M}}{\partial t}\right)_{Non-Adiabatic}^{STT} = \beta \vec{M} \times ((\vec{u} \cdot \nabla) \vec{M}), \quad (46)$$

where β is the non-adiabaticity constant. Both **STTs** can be added to the **LLG** equation (42) to describe the dynamics of a magnetic system in the presence of applied fields and charge currents [177]:

$$\begin{aligned} \frac{\partial \vec{M}}{\partial t} = & -\gamma_G (\vec{M} \times \vec{H}_{Eff}) + \underbrace{\frac{\alpha_G}{M_S} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right)}_{\text{Damping}} - \underbrace{(\vec{u} \cdot \nabla) \vec{M}}_{\text{Adiabatic}} \\ & + \underbrace{\beta \vec{M} \times ((\vec{u} \cdot \nabla) \vec{M})}_{\text{Non-Adiabatic}}. \end{aligned} \quad (47)$$

Adiabatic and non-adiabatic **STTs** are naturally present in the measurement scheme as the current also flows in the **FM** layer, however the current density to manipulate the magnetization is usually one order of magnitude larger as compared to the **SOT** ($\approx 10^{12}$ A/m² [135]).

Spin-Orbit Torque

The **SOT** can be introduced as a current-induced effective field, $\Delta \vec{H}$, into the **LLG** equation [Eq. (42)] which gives

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times (\vec{H}_{Eff} + \Delta \vec{H}) + \frac{\alpha}{M_S} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right). \quad (48)$$

Zhang et al. [178] showed that a spin accumulation transverse to the local magnetization acts as a polarizer layer in a similar way as a reference layer acts in spin valves / **MTJs** which is given by

$$\begin{aligned} \frac{d\vec{M}}{dt} = & -\gamma_G \vec{M} \times \vec{H}_{Eff} - a \vec{M} \times \hat{p} - b \vec{M} \times (\hat{p} \times \vec{M}) \\ & + \frac{\alpha_G}{M_S} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right). \end{aligned} \quad (49)$$

$\hat{p}$ is the unit vector of the incoming spin current into the **FM** layer which results in a spin accumulation acting on the local magnetization. a and b are constants with respect to $\vec{M}$ which are related to material parameters and current as [178]

$$a = \frac{h J a_0^3 \gamma}{\sqrt{2} e \mu_B \lambda} \left(\frac{1 - \cos D e^{-D}}{D} \right), \quad (50)$$

$$b = -\frac{hJa_0^3\gamma}{\sqrt{2}e\mu_B\lambda}\left(\frac{\sin De^{-D}}{D}\right). \quad (51)$$

h is the Planck constant, J is the current density, $D = t_F/(\sqrt{2}\lambda)$, a_0 is the lattice constant and λ is the spin diffusion length. The two torques related to a and b are called fieldlike torque [178] and dampinglike torque [178, 142, 9]. The corresponding effective fields for the fieldlike and dampinglike torque are given by ($\gamma_G = \gamma$)

$$\vec{H}_{FL} = \frac{a}{\gamma}\hat{p}, \quad (52)$$

$$\vec{H}_{DL} = \frac{b}{\gamma}\hat{p} \times \vec{M}. \quad (53)$$

As such, the fieldlike field $\vec{H}_{FL}$ is considered a constant field independent on the magnetization whereas the dampinglike field $\vec{H}_{DL}$ depends on the magnetization.

1.6 DETECTION OF MAGNETIZATION MANIPULATION

1.6.1 Hall effect

The Hall effect is based on the Lorentz force where a charge current in a conductor experiences a force when an external magnetic field $\vec{B}$ is applied perpendicular to the charge current with velocity $\vec{v}$. This is exemplified in Fig. 17. The resulting force is described by the Lorentz

Figure 17: Schematic of Hall effect.

force as

$$\vec{F} = -e\vec{v} \times \vec{B}. \quad (54)$$

The Lorentz force can be directly detected as a transverse voltage (Hall voltage) as $V_H = vB\Delta y \cos \alpha$ with α the angle between $\vec{v}$ and $\vec{B}$. For externally applied out-of-plane fields, B_z , the Hall voltage adds a small contribution to the leading contribution related to the AHE at room temperature in microstructures.

1.6.2 Anomalous Hall effect

The AHE, while discovered more than 100 years ago, is still not fully understood. Recent advances in the description of the SHE have greatly helped in the understanding of AHE which is considered to be from the same origin as the SHE. The phenomenon describes the induced transverse charge-spin current due to a spin-polarized charge current, as shown in Fig. 18. No external $\vec{B}$ -field is required which distinguishes this effect from the Hall effect. The effect is illustrated in Fig. 18. The

Figure 18: Schematic of anomalous Hall effect.

transverse Hall resistance is given by [120]

$$R_H = \Delta R_A \cos \theta, \quad (55)$$

with $\Delta R_A = \frac{C}{t_F} M_S$ the AHE resistance, C is a constant related to the AHE, t_F is the thickness of the magnetic material and θ the angle of the magnetization with respect to the surface normal.

1.6.3 Planar Hall effect

The PHE is based on the AMR. The AMR can be usually described by an electric field as [127, 100]

$$\vec{E} = \rho_{\perp} \vec{J} + (\rho_{\parallel} - \rho_{\perp}) \hat{m} (\vec{J} \cdot \hat{m}), \quad (56)$$

where $\vec{E}$ is the effective electric field in the magnetic structure, $\vec{J}$ is the current density applied to the magnetic structure, $\rho_{\perp}$ is the resistivity when the magnetization vector is orthogonal to the current density, $\rho_{\parallel}$ is the resistivity when the magnetization vector is parallel aligned to the current density and $\hat{m}$ is the unit magnetization vector. If we define the magnetization angles as in Fig. 19 and fix the current density in x-direction, the electric field components for x- and y-directions can be computed as

$$E_X = \rho_{\perp} J + (\rho_{\parallel} - \rho_{\perp}) J \sin^2 \theta \cos^2 \varphi, \quad (57)$$

Figure 19: Schematic of planar Hall effect.

$$E_Y = (\rho_{\parallel} - \rho_{\perp}) J \sin^2 \theta \cos \varphi \sin \varphi. \quad (58)$$

E_X is related to the AMR whereas E_Y is the so-called PHE. The transverse electric field E_Y can be reformulated in terms of the Hall voltage as [120]

$$R_H = \Delta R_P \sin^2 \theta \sin 2\varphi, \quad (59)$$

where $\Delta R_P = k \frac{M_S^2}{t_F}$ is the resistance change due to PHE and k is a constant.

1.6.4 Spin Hall magnetoresistance

While it is not yet clear what is the cause of the SMR, the most prominent results focus on a SHE-induced proximity effect which helped explaining some results for a ferromagnetic insulator (FI)/NM bilayer structure in particular the yttrium iron garnet (YIG)/Pt interface [163, 65, 112]. The induced resistance is then measurable *via* the inverse SHE where a pure spin current induces a transverse charge current [30]. Others try to give an explanation by the edge spin accumulation itself providing a magnetoresistance in a magnetic field [39], Hanle effect [158] or interfacial spin-orbit scattering [179]. As such, I will just reproduce the relationship to observe the magnetoresistance effect which is given for a current flowing in x-direction, as shown in Fig. 19 for the PHE [112]:

$$R_X = R_0 - \Delta R_S m_y^2 = R_0 - \Delta R_S \sin^2 \theta \sin^2 \varphi, \quad (60)$$

$$R_Y = R_H = \Delta R_S m_x m_y = \Delta R_S \sin^2 \theta \sin 2\varphi. \quad (61)$$

R_0 is the electrical resistance of the wire and ΔR_S is the resistance change due to SMR effect. Hence, this effect exhibits the same symmetry as the PHE resistance for Hall resistance configuration. One might need to measure the longitudinal resistance to distinguish both effects from each other. The SMR has also been implemented into purely metallic heterostructures recently, which shows non-negligible SMR in the NM/FM layer heterostructures [77, 85].

DEVICE FABRICATION AND EXPERIMENTAL SETUP

In this chapter, the process of the sample fabrication and the functional principle of the measurement setup is explained.

2.1 DEVICE FABRICATION

Subsequent patterning into Hall bar structures was performed using a combination of resist spin coating, electron beam lithography (EBL), development, argon ion milling and stripping. Finally, the contact pads were sputtered and lift-off procedure from the resist was performed.

2.1.1 *Film sputtering*

As a negative photoresist is used to pattern the device structure, magnetron sputtering was initially performed to deposit the thin film materials onto 300 nm oxidized (SiO₂) silicon substrate wafers. The thin films were grown in a commercial AJA sputtering system at a base pressure of $\sim 2 \times 10^{-8}$ Torr and a working Ar pressure of 3 mTorr at 50 W. An image of the AJA sputtering system is shown in Fig. 20. The target to substrate distance was 4 cm for the thin films. As shown in Fig. 21, after reaching a high vacuum state, Ar gas is pumped into the chamber. A high voltage accelerates the 'ever existing' free electrons away from the cathode (target).

Figure 20: Image of AJA magnetron sputtering system used.

To increase the sputtering rate, the electrons are trapped in a magnetic field near the target. The electrons will collide with electrons of the outer shell of the Ar atoms and ionize the Ar atoms to Ar^+ ions which are accelerated towards the cathode. The electrons from the Ar atoms are again accelerated away from the cathode and keep the plasma state ongoing. The positively charged Ar^+ ions are accelerated towards the cathode where they kick out clusters of target atoms. While being electrically neutral, the kicked out clusters of target atoms travel to the opposite side where they accumulate onto the substrate. The uniformity of the accumulated target atoms depends on parameters such as crystallinity and lattice constant of the substrate and target material, mean free path length of the target atoms and target to substrate distance.

The contact pads of around Ta(5 nm)/Cu(100 nm)/Au(20 nm) were sputtered in a different chamber with ~ 15 cm target to substrate distance. The base pressure was between 5 to 10×10^{-8} Torr and a working pressure of ~ 4 to 7 mTorr. All films deposited were sputtered by direct current (DC) except the barium titanate (BaTiO_3) (BTO) film which was sputtered by radio frequency (RF). The RF sputtering technique has been used for the barium titanate film because as an insulating material, positive charges can accumulate on the dielectric material which might lead to secession.

The thickness of the films were determined by a pre-calibrated sputtering rate for each target times the sputtering time. The sputtering rate for each target was determined by sputtering a long period of time and subsequently measuring the film thickness with atomic force

microscopy (for short sputtering periods the sputtering rate can be estimated as linear).

Figure 21: Schematic of a magnetron sputtering chamber.

2.1.2 Device patterning

After deposition of the thin films ma-N 2403 negative electron beam resist was spin coated onto the samples using 6000 rpm for 60 s which ensures a laminar coating of less than 200 nm.

Figure 22: Fabrication steps of device patterning.

The resist was subsequently baked for 60 s at 100 °C. After baking, EBL using a commercial Raith *e – line* EBL system was performed, as shown in Fig. 22 (c). An image of the Raith *e – line* system is shown

in Fig. 23. The Hall structure layout was drawn using the graphic database system (GDS)II-editor prior to the electron beam exposure.

Figure 23: Image of *Raith e-line* system for electron beam lithography procedure.

After completion of electron beam exposure, the sample was solved in ma-D developer which removes the non-exposed resist from the sample, as shown in Fig. 22 (d). To mill the structure into the thin film, Ar^+ ion milling was executed. An image of the *AJA* ion milling system used is shown in Fig. 24. Similarly to sputtering, the Ar^+ ions will kick out atoms from both the exposed resist as well as the facing thin film, as shown in Fig. 22 (e). As the thin film is usually in the order of ~ 20 nm whereas the resist and the underlayer of SiO_2 are in the order of 200 to 300 nm, the samples were overetched which results in a non-uniform SiO_2 film. However this is not problematic in our case as the patterned magnetic structure is protected by the resist and therefore does not experience any harm.

Figure 24: Image of AJA ion milling system used.

The exposed resist can be removed from the structure by stripping for ~ 6 hours in *micro resist (technology) Remover (mr-Rem)* remover in an ultrasonic bath to improve the removal of the resist.

The contact pads are deposited in a similar procedure using positive 4 % 950 k molecular weight of polymethyl methacrylate in anisole (*PMMA*) resist. The resist was spin coated at 4000 rpm for 45 s and post-baked at 180°C for 5 min. Then, *EBL* was performed which exposed the contact pad structures into the resist. The exposed resist was removed by a isopropyl alcohol ($\text{C}_3\text{H}_8\text{O}$) (*IPA*)/methyl isobutyl ketone (*MIBK*) solution in a ratio of 3:1 for 30 s. The contact pads were fabricated by magnetron sputtering system, as explained in section 2.1.1. The positive resist was then easily removed by lift-off procedure in acetone.

2.2 HARMONIC HALL MEASUREMENT SETUP

In order to conduct *AC* magnetotransport measurements, the following equipments have been used:

- AC-DC *Keithley 6221* current source
- *SignalRecovery 7265* Dual Phase digital signal processor (*DSP*) lock-in amplifier
- Electromagnet with power supply (~ 8 A)
- Manual stage for 360° rotation
- *NationalInstrument's* Labview software for data acquisition and equipment handling

- *Hirst* GMo8 Gaussmeter
- *Quantum Design's* rotator sample board

Figure 25: Schematic of the harmonic Hall measurement technique.

A schematic of the Hall structure with the connection is shown in Fig. 25 where the AC current source is connected to the wire long axis and the Hall bars are plugged into the lock-in amplifier. The experimental setup is shown in Fig. 26. The patterned structure on the substrate is mounted on the rotator sample board. Then, the contact pads on the device are wire bonded onto contact pads on the sample board. The sample board is clipped to the counterpart which connects directly to cables. The counterpart of the sample board was fixed onto the manual stage, as shown in Fig. 26. The manual stage with the device can then be mounted between the two coils of the electromagnet. As the device is rotated within the electromagnet, special attention has to be given to place the device at the center between the two coils. As the area of the coils exceed the length of the sample board, a laminar externally applied magnetic field then can be expected during the measurement. Subsequently, the cable for the Hall bar is connected to the front channel, *A*, of the lock-in amplifier, as indicated in Fig. 26. The cables of the wire long axis are connected to the current source channel at the back of the AC-DC *Keithley* current source. Additionally, the current source is connected to the transistor-transistor logic (TTL) channel of the lock-in amplifier which provides the lock-in amplifier the signal of the AC frequency. The Gaussmeter is finally placed over the sample board, centered between the two coils of the electromagnet, as shown in Fig. 26. The distances to the coils of the Gaussmeter and the device should be equal. All electronic equipments are connected to a computer with a Labview software code which controls all the equipments simultaneously used for the harmonic Hall voltage measurement.

Figure 26: Image of the experimental setup and equipments used for harmonic Hall measurement.

Parameters used in the harmonic Hall voltage scheme usually are maximum coil current and current step size for the electromagnet, amplitude of AC current source and number of data points averaged per voltage data point, as well as the current source frequency. The acquired data includes the first and second harmonic Hall voltages as well as the magnetic field values from the Gaussmeter.

For out-of-plane field measurement, a different sample board was employed which allows for a fixed out-of-plane configuration within the two coils of the electromagnet.

CONCURRENT QUANTIFICATION OF SPIN-ORBIT TORQUE EFFECTIVE FIELDS

In this chapter, the harmonic Hall voltage technique to quantify *SOT* fields and field-driven *DW* depinning fields at various *AC* bias currents are compared. By comparing both techniques, we identify the *PHE*-symmetry in the harmonic Hall voltage technique as a crucial factor which requires the recently introduced *PHE* correction [61]. Anisotropy and coercivity field are also found to decrease with increasing current density in the wire which is attributed to *SOT* effective fields. This chapter has been reproduced from published work in *Journal of Applied Physics* with the permission of *AIP Publishing* [43].

3.1 MOTIVATION

SOC in structures comprising of a *HM* adjacent to a *FM* leads to an in-plane charge current inducing orthogonal pure spin current *via* bulk *SHE* in the *HM* and an effective field *via* Rashba effect at the interface. The pure spin current transfers its spin angular momentum to the *FM* *via* *SOT* which comprises of dampinglike and fieldlike torques [76, 92, 124]. The *SOT*-induced by *SHE* has been proposed as an alternative writing mechanism in *MRAM* devices. The read and write paths can be decoupled in the proposed three-terminal *MTJ* [93] while improving the reliability of the memory device [93, 67]. Various methods to quantify *SOT* effective fields have been developed such as magnetization switching [104, 105], *DWM* [41, 135, 56], *MOKE* [48], spin-torque *FMR* [91, 49] and *AC* Hall voltage [130, 53, 76, 61] techniques. However, contradicting results have been reported in similar material systems using different techniques [93, 153]. This asks for cross-checking of various quantification methods and their usefulness. New systems have been introduced to achieve deterministic *SOT*-induced magnetization switching in *FM* systems with *PMA* using an in-plane external magnetic field [56]. To create this intrinsic in-plane field, different methods have been proposed; the utilization of an external in-plane field, a tilted magnetic *FM* layer leading to an unbalance of the out-of-plane anisotropy and the introduction of an *AFM* which produces a current dependent in-plane exchange bias field to the *FM* layer. The externally applied in-plane field breaks the symmetry and is able to reverse the magnetization [92, 93, 105]. Similarly, the tilted *FM* layer may produce through an inhomogeneous magnetic out-of-plane anisotropy an intrinsic effective in-plane field which helps in breaking the symmetry for magnetization switching [174]. The use

of an AFM with in-plane exchange bias also has been shown to lead to deterministic magnetization switching [52, 79, 85, 157]. The intrinsic magnetic material properties are incidentally affected by the attached AFM layer. To study SOTs in such systems with adjacent AFM layer and to cross-check the validity of the SOT determination, the SOT effective fields have been determined in the same system using concurrent quantification techniques such as AC harmonic Hall voltage method and depinning field method.

3.2 EXPERIMENTAL DETAILS

A HM/FM/AFM stack was grown by DC magnetron sputtering at room temperature on 300 nm thick SiO₂ on Si substrates. The stack structure comprises of SiO₂/Ta (5)/Pt (5)/[Co (0.25)/Ni (0.5)] $\times$ 4/Co (0.25)/iridium manganese (IrMn₃) (IrMn) (10)/Ta (5) where the numbers in brackets correspond to the respective film thicknesses in nm. No field or heat treatment has been carried out after deposition of the film. The out-of-plane magnetization (M - H) loop obtained using polar MOKE for the HM/FM/AFM stack is shown in Fig. 27 (a).

Figure 27: (a) Normalized polar MOKE signal as a function of the applied field along the film normal of the bulk film comprising of the stack Pt/(Co/Ni)₄/Co/IrMn. (b) Normalized Hall resistance signal as a function of the applied field along the film normal of the bulk film comprising of the stack Pt/(Co/Ni)₄/Co/IrMn.

The as-grown HM/FM/AFM film exhibits a clear out-of-plane magnetic anisotropy with a coercivity of 265 Oe and an out-of-plane exchange bias field of 145 Oe. The magnetization switching in the negative field occurs at much higher magnitude compared to the positive field. This can be explained by the EB field from the AFM layer promoting magnetization alignment along the +z-axis orientation. The film is patterned into 4 μ m wide and 70 μ m long wire *via* EBL. Hall bar contacts comprising of Ta/Cu/Au were patterned transverse to the wire orientation, along the y-axis, as shown in Fig. 28.

Figure 28: A schematic and SEM image of the Hall bar structure.

Magnetotransport measurements were carried out in order to investigate the effect of bias current on the magnetization of the [HM/FM/IrMn](#) stack [130, 61]. For this measurement, a *Keithley 6221 AC* current source was used to apply the [AC](#). The harmonic Hall voltages were measured using a 7265 Dual Phase [DSP](#) lock-in amplifier. For all the measurements, the [AC](#) frequency was set to 309 Hz to allow for an adiabatic change of the magnetization vector. Magneto-Optical Kerr imaging was performed while sweeping an external field in the out-of-plane orientation.

3.3 EFFECT OF BIAS CURRENT ON SWITCHING FIELD

Coercivity and exchange bias field of the patterned wire were first investigated as a function of externally applied fields and [AC](#) bias. The Hall resistance (R_H) was measured *via* [AHE](#) by sweeping the applied magnetic field perpendicular to the plane of the wire, H_Z . The Hall resistance R_H of the wire as a function of applied magnetic field H_Z , (R_H - H_Z loops) for an [AC](#) channel current of 1 mA is shown in Fig. 27 (b). From the [AHE](#) loop, the magnetization switching of the wire occurs at an external field of +300 Oe and -400 Oe respectively. This implies that the coercivity of the patterned wire is 350 Oe while the [EB](#) field is estimated to be -50 Oe. As expected, the coercivity of the patterned wire exhibits an increase, of ~ 85 Oe, as compared to the bulk film. The decrease in the [EB](#) field is attributed to the patterning process.

Figure 29: Differential polar magneto-optic Kerr imaging microscopy images as a function of applied out-of-plane magnetic fields. (i-iii) grey color corresponds to down magnetization ($-M_z$) and the white color corresponds to up magnetization ($+M_z$). (iv-vi) the grey color corresponds to up magnetization ($+M_z$) and the black color corresponds to down magnetization ($-M_z$).

In order to understand the magnetization reversal process in the wire, *in-situ* differential Kerr microscopy was carried out while varying the externally applied field, H_z , as shown in Fig. 29. Reference Kerr images are first taken at positive and negative saturation field. The subsequent magnetic images are then obtained by subtracting the Kerr images from the reference image. As such, for no magnetization switching with respect to the reference, the corresponding differential Kerr image results in no magnetic contrast, corresponding to grey color in the Kerr image. At remanence, a grey color is observed, corresponding to the initial magnetization configuration being along the $+z$ - or $-z$ -axis orientation. For Figs. 29-i to iii the wire was initially magnetized along the $-z$ -axis by first applying an out-of-plane field of -1.4 kOe. The reference Kerr image was taken at -1.4 kOe, as shown in Fig. 29-i. Subsequently, the externally applied field is ramped up along the $+z$ -axis direction where oppositely magnetized domain, characterized by the bright contrast in Fig. 29-ii, is nucleated in the wire, at external field of 140 Oe. This is consistent with the switching field obtained from the R - H loop in Fig. 27 (b). The reversed domain nucleates from the edge of the wire due to a reduction in the out-of-plane anisotropy at the edges of the wire from defects induced during patterning [12]. Further increase in the external field leads to the expansion of the reversed domain, resulting in complete magnetization switching of the wire, Fig. 29-iii. For Figs. 29-(iv to vi), the wire was initially magnetized along $+z$ -axis orientation with an out-of-plane field of $+1.4$ kOe and thereafter the field was ramped along $-z$ -axis direction. Using the state obtained at $+1.4$ kOe, Fig. 29-iv as a reference, grey color at no magnetization reversal is imaged. As the externally applied field is increased in the $-z$ -axis direction,

the reversal process occurs via nucleation and propagation of reversed domain in the wire, as seen by the dark contrast in Fig. 29-v. The expansion of the reversed domain results in complete magnetization switching. The Kerr image of Fig. 29-vi corresponds to the complete magnetization reversal of the wire, resulting in a saturation state with a complete dark contrast. The Kerr imaging reveals that irrespective of the initial magnetization configuration, the switching process is *via* reversed DW nucleation and DWM along the wire.

To investigate the effect of current on the magnetization reversal process of the wire, the AC current amplitude was varied from 1 to 12 mA, corresponding to current densities of $8.9 \times 10^9 - 1.1 \times 10^{11} \text{ A/m}^2$. An AC source probing is chosen as it enables better signal-to-noise ratio (SNR) due to the use of lock-in system and also, it minimizes the Joule heating effect in the wire. The coercivity and exchange bias field are extracted from the AHE loops and are plotted as a function of the applied current, as shown in Fig. 30. The coercivity decreases monotonically as the current is increased, from 350 to 120 Oe as the current magnitude is increased from 1 to 12 mA. On the other hand, the exchange bias field remains almost constant at $\sim -55 \text{ Oe}$ for the current range investigated.

Figure 30: Extracted coercivity and exchange bias fields from the Hall resistance hysteresis loop of the wire as a function of different AC current.

From the Kerr imaging, it can be inferred that the measured coercivity in the AHE loop of the Fig. 27 (b) is correlated with the DWM along the wire direction (x-axis). The coercive field obtained from the AHE measurement can then be viewed as being the field required to depin the DW and pin the DW at the Hall bar. Current-induced DW depinning field decrease has been reported for wires with both in-plane and out-of-plane magnetic anisotropy [60, 132]. The current leads to DW transformation *via* spin momentum transfer, resulting in a reduction of the depinning field [132, 33]. For FM/HM stack, where the SOT is dominant, the reduction in depinning field has been attributed to the

dampinglike effectively field from the SOT [103]. For wires with FM/Cu stacks, no change in depinning field was reported [103]. In structures with out-of-plane magnetic anisotropy, the dampinglike field can be read as $\vec{H}_{DL} \sim \vec{M} \times \hat{z} \times \hat{j}$ where $\hat{j}$ is the unit vector in current direction, $\hat{z}$ the unit vector along the z-axis and $\vec{M}$ the magnetization vector. The dampinglike field acts along the current direction which is directed along the x-axis providing a torque transverse to the x-axis and the magnetization direction ($\vec{\tau} \approx \vec{H}_{DL} \times \vec{M}$) [94]. As the applied current is increased, the dampinglike field increases proportionally, resulting in the DW internal spin aligning along the dampinglike field orientation. The contribution of Joule heating on the reversal process can be neglected here, as the resistance change of the wire was negligible as the current was increased.

3.4 PROBING OF CURRENT-INDUCED DOMAIN WALL DEPINNING FIELD MODULATION

To quantify the current-induced torques, the SOT effective fields in the system were characterized using the conventional Hall harmonic measurement technique [130]. As conventional harmonic Hall technique probing SOT effective fields only holds valid in the vicinity of a single magnetic domain, field-induced DW depinning at the Hall cross was utilized in order to cross-check the validity of conventional harmonic Hall measurement. STT might also be present at such small current densities, however the main contribution is expected from the SOT in the heterostructure [149, 81, 155, 105, 138]. In-plane magnetic field sweeps were performed in order to obtain the SOT effective fields acting longitudinal (in x-direction) or transverse (in y-direction) to the long axis of the wire. In our stack we expect the SOT effective fields to originate from both the Pt layer and the IrMn layer. The first harmonic Hall voltage, V_ω , for a PMA wire is given by [61]:

$$V_\omega \approx \pm \frac{1}{2} \Delta R_A \left[1 - \frac{1}{2} \left(\frac{H \sin \theta_H}{H_K \pm H \cos \theta_H} \right)^2 \right] I_{ac}, \quad (62)$$

where ΔR_A is the AHE resistance, H_K the effective anisotropy field, H is the externally applied field and θ_H is the external field angle with respect to the film plane normal (here $\theta_H \approx 90^\circ$ for in-plane field sweeps). The $\pm$ sign indicates the magnetization orientation along the $\pm z$ -axis direction. For all measurements, an AC bias current was applied in the wire. The representative Hall resistance (R_H) for an AC bias current of 5 mA, as the magnetic field was swept along the x-direction, is shown in Fig. 31 (a).

Figure 31: First harmonic Hall resistance as a function of the applied field. The field was swept within a field range of ± 2.8 kOe with an AC bias current of 5 mA. (a) The field sweep was along the x-axis direction. (b) The field sweep was along the y-axis direction.

Two field sweeps were performed: positive field sweep where the magnetic field is swept from zero to maximum positive field, followed by a field sweep from maximum positive to maximum negative and then back to zero. For the negative field sweep, the magnetic field is swept from zero to maximum negative, then to maximum positive and finally to zero. For field sweep within the range of $+2$ kOe to -2 kOe, the Hall resistances display a parabolic trend for both magnetization orientations ($\pm z$) of the wire, as predicted by Eq. (62). For large external field sweeps, $|H| > 2$ kOe, a sharp change in Hall resistance is observed at ± 2.2 kOe as can be seen in Fig. 31 (a). When the sample is magnetized along the $-z$ -axis, a sharp jump in Hall resistance is observed at $+2.2$ kOe. Similarly, for sample magnetized along the $+z$ -axis, a sharp drop in Hall resistance value is noted at -2.2 kOe. The increase/decrease in the Hall resistance at ± 2.2 kOe, results in almost similar Hall resistance magnitude, mid-way between the Hall resistance values obtained for $+z$ - and $-z$ -axis oriented saturation magnetization, as seen in Fig. 31 (a). This midway Hall resistance comprises of the equal contributions in resistance from magnetization vectors aligned in the $+z$ - and $-z$ -axis direction, corresponding to a half-switch state. Further field sweeps result in negligible change in the Hall resistance magnitude, implying that the half-switched state is a stable configuration at the Hall bar. The half-switched state is attributed to the presence of a pinned DW at the Hall cross. This can be further manifested by measuring the second harmonic Hall resistances simultaneously, as shown in Fig. 33. The field sweeps were started from initially in $+z$ -axis direction magnetized state (a) or $-z$ -axis direction in (b) at 0 Oe. Subsequently, the applied field amplitude was ramped up in the x-axis direction according to the red arrow direction. While the first harmonic Hall resistances exhibit the parabolic relationship with the applied field, the second harmonic Hall resistances have a linear relationship with respect to the applied field, as explained in section 3.5. After the depinning of the DW, the second harmonic Hall resistance follows a linear trend with larger slope as compared to the

linear behavior before the depinning. This slope is an indication that the wire is not in a demagnetized state where no second harmonic Hall signal is expected. Also, the switch to an in-plane magnetization configuration, which also could be responsible for a first harmonic Hall resistance state between the $\pm z$ -axis magnetized states. However, the second harmonic Hall resistance, then, follows another relationship as explained elsewhere [61, 96]. This observation is consistent with the imaged *DWM* in section 3.4.

The combination of current and external in-plane field induces magnetization reversal leading to the propagation of *DW* within the wire.

Figure 32: Schematic configuration of Bloch and Néel domain wall types in a ferromagnetic structure. The Bloch wall is symmetric under a 180° rotation along the transverse axis to the wire whereas the Néel wall rotates along the wire axis. At the bottom image shows the contributions of spin current from the Pt underlayer to the domain wall.

As the external field is applied along the x -axis, a chiral Néel *DW* configuration is favored. The chirality of the Néel *DW* is determined by the initial orientation of the magnetization and the *DMI* induced by the *AFM* layer [170, 152] or the interface between sublayer/*FM* layer. In our film stack comprising of Pt/Co and interfaces, a left-handed chiral Néel *DW* is expected to be stabilized. [25]. For samples with initial magnetization along the $+z$ -axis, the Hall resistance change occurs for external fields applied along the $-x$ -axis, as seen in Fig. 31 (a). This implies that the *DW* propagates through the wire when the external magnetic field is applied along the $-x$ -axis. For external fields up to $+2.8$ kOe, applied along the $+x$ -axis, no resistance drop, corresponding to no *DWM*, was observed. This is consistent with the in-plane field-induced *DW* propagation of a left-handed Néel *DW* with Up-Down configuration ($\uparrow\leftarrow\downarrow$). As shown in Fig. 32, within Néel *DWs* a gradual change of their magnetization components along the wire long axis are observed, where the resulting dampinglike field at the *DW*

has an out-of-plane field component (H_z) [99]. Thus, the dampinglike field is accountable for magnetization reversal in the structure as it produces an out-of-plane field component that drives the DW. For field swept along y-axis, same parabolic trend is expected for the first harmonic voltage. Shown in Fig. 31 (b) is the first harmonic Hall voltage measured with an AC bias current of 10 mA flowing through the wire.

Figure 33: First and second harmonic Hall resistances as a function of magnetic field swept longitudinal to the wire while depinning of a domain wall. The AC bias in the wire was 10 mA. First harmonic Hall resistance for sample initially magnetized along (a) +z-axis and (b) -z-axis orientation. The respective second harmonic Hall resistances are shown in (c) for +z-axis and (d) for -z-axis oriented magnetization.

For field swept initially of up to -2.2 kOe or $+2.2$ kOe, the Hall resistance follows a parabolic trend as expected from Eq. (62). Further increase in the magnetic field in the positive (negative) -y-axis direction, leads to a sharp drop (jump) in the Hall resistance for samples magnetized along +z (-z)-axis orientation. Similarly to Fig. 31 (a), the drop (jump) in Hall resistance value results in a magnitude which is midway between the maximum and minimum Hall resistance values. Subsequent field sweeps do not influence the Hall resistance significantly. As discussed previously, a DW pinned at the Hall cross may account for the stable Hall resistance value. Interestingly, for the magnetic field swept transverse to the long axis of the wire, both the maximum positive and maximum negative field sweep result in a drop (jump) in Hall resistance. This implies that the DW within the wire can be driven by both orientations of applied fields, which was not observed in Fig. 31 (a). The transverse applied field might transform the DW to a Bloch DW configuration within the wire. This

allows bidirectional motion of the DW as a function of the current and transverse field orientation. For fields applied along the +y-axis, transverse to the wire, the AC bias current was varied from 1 to 11 mA in the wire. The measured Hall resistance, for samples magnetized along the +z-axis at AC bias current of 1 mA and 11 mA, is shown in Fig. 34 (a). As the amplitude of the current was increased, the Hall resistance drop occurs at lower external fields. This drop in the Hall resistance corresponds to the depinning field of the DW which is pinned at the Hall cross instantaneously.

Figure 34: (a) Hall resistance drop for a bias current of 1 and 11 mA with magnetic field applied along the +y-axis direction. The depinning fields were calculated by taking the difference of the magnetic fields at which 50 % of the resistance drop occurs. (b) The difference in transverse depinning field as a function of the AC bias current density with reference current density at 8.9×10^9 A/m².

The shift in the depinning field implies that the DW reaches the Hall cross at much lower external field as the current in the wire is increased. The dynamics of the DW is then governed by the external magnetic field and applied current induced SOT effective fields in the wire. As such, any shift in the DW depinning field is an indicator of the current induced torque on the DW dynamics in the wire. The depinning field corresponds to the external field where 50 % of magnitude of the Hall resistance drop occurs. Using the DW depinning field at a bias current of 1 mA as reference (H_1 in the Fig. 34 (a)), the difference in depinning field, ΔH_{Depin} , as a function of different AC bias current is computed. For example, the depinning field for a bias current of 11 mA is given by $\Delta H_{Depin}(11 \text{ mA}) = H_1 - H_{11}$. Shown in Fig. 34 (b) is the depinning field difference as a function of the applied current density. A quasi-linear trend is observed for high current magnitudes. The difference in external field ΔH_{Depin} to depin the DW in the system for a current density of 8.3×10^{10} A/m², which translates to an effective current density of 7.4×10^{10} A/m² with respect to the reference at 0.9×10^{10} A/m², is calculated to be $400 \text{ Oe} \pm 50 \text{ Oe}$. We postulate that this difference in external field, ΔH_{Depin} , can be attributed to the fieldlike term of the SOT. The fieldlike field aligns collinearly with the externally applied magnetic field which is swept transverse to the wire

long axis in y-axis direction Any increase in the fieldlike field due to current increase will be subtractive to the external field, as shown in Fig. 34 (a). Consequently, the fieldlike field can be extracted from first harmonic Hall voltage measurement by exploiting DWM and pinning at the Hall cross. Using similar approach as compared to field assisted DW depinning with STT, where the depinning efficiency is given by $\chi = \Delta H_{Depin} / \Delta J$, [99, 41], the depinning efficiency for SOT assisted DW depinning efficiency can be computed. From Fig. 34 (b), the SOT efficiency ($\chi = \Delta H_{Depin} / \Delta J$), for the fieldlike field is calculated to be $\sim 63.7 \text{ Oe} / (10^{10} \text{ A/m}^2)$.

3.5 HALL MEASUREMENTS TO INVESTIGATE ANISOTROPY AND SOT EFFECTIVE FIELDS

To quantify the SOT effective fields, first (V_ω) and second ($V_{2\omega}$) harmonic Hall voltages were measured as a function of applied in-plane magnetic fields, as shown in Fig. 35. As expected, the first harmonic Hall voltages, V_ω , show parabolic relationships with respect to the applied field whereas the second harmonic Hall voltages, $V_{2\omega}$, show linear relationships with the applied field. The maximum applied field amplitude was kept to 1.1 kOe not to cause a DW depinning, as discussed in section 3.4. For sample initial magnetized along $\pm z$ -axis, both second harmonic Hall voltage slopes ($b_{2\omega,X} = \partial V_{2\omega} / \partial H_X$) reveal identical slopes separated by an offset voltage for field applied longitudinal to the wire long axis. For the field sweeps in y-axis direction, the second harmonic Hall voltage slopes ($b_{2\omega,Y} = \partial V_{2\omega} / \partial H_Y$) reverse sign as the initial magnetization is changed from $+z$ -axis to $-z$ -axis magnetized state, in line with other observations [76, 61, 167]. The first harmonic Hall voltages in Figs. 35 (a) and (b) were fitted by a parabolic function which provides a fitting parameter comparable to the second derivative as $b_{\omega,X,(Y)} = \partial^2 V_\omega / \partial H_{X,(Y)}^2$. The second harmonic Hall voltages, $V_{2\omega}$, are fitted by a linear function which provides a fitting parameter comparable with the first derivative after the applied field as $b_{2\omega,X,(Y)} = \partial V_{2\omega} / \partial H_{X,(Y)}$.

Figure 35: (a), (b) first harmonic Hall voltages as a function of the applied in-plane field at 10 mA bias current in the wire. (a) shows the Hall voltage with field pointing along x-axis direction and (b) with field pointing along y-axis direction. (c), (d) second harmonic Hall voltages as a function of the applied in-plane field. (c) shows the Hall voltage with field pointing along x-axis direction and (d) with field pointing along y-axis direction.

The effective **SOT** fields, dampinglike (H_{DL}) and fieldlike (H_{FL}), can be extracted from the derivatives of the first and second harmonic Hall voltages with respect to the applied field as [76]

$$H_{DL,(FL)} = -2 \frac{b_{2\omega,X,(Y)}}{b_{\omega,X,(Y)}}. \quad (63)$$

The dampinglike field, H_{DL} , was extracted from the Hall voltage measurements while sweeping an external magnetic field along the x-axis direction for various **AC** bias current in the wire, as shown in Fig. 36. The fieldlike field, H_{FL} , was obtained from the external field sweeping along the y-axis direction. A linear trend in H_{DL} is observed, which is in agreement with previous reported results [76, 18]. For a current density of 8.3×10^{10} A/m² the effective dampinglike field for magnetization aligned along $-z$ -axis is 61 Oe, whereas for magnetization oriented along the $+z$ -axis, the effective field is 67 Oe. The difference between the effective dampinglike field with up ($+z$) and down ($-z$) magnetization can be attributed to slight variation within the measurement setup. From Eq. (62) the effective anisotropy field H_K of the **FM** layer can also be derived as a function of the current

density in the wire. Using the fitting parameter $b_{\omega,X} = \partial^2 V_{\omega} / \partial H_X^2$ and $\theta_H = 90^\circ$ for externally applied in-plane fields, the effective anisotropy field H_K is computed as

$$H_K \approx \sqrt{\frac{I_{ac} \Delta R_A}{2b_{\omega,X}}}. \quad (64)$$

The AHE resistance, ΔR_A , is calculated from Eq. (62) as $\Delta R_A = R_{H,max} - R_{H,min}$ to $0.220 \Omega \pm 0.003 \Omega$. The computed effective anisotropy field, H_K , from Eq. (64), is plotted field sweep in x-axis direction in Fig. 36 (b).

Figure 36: (a) Dampinglike effective field for both magnetization orientations as a function of the AC in the wire. (b) Out-of-plane anisotropy effective field for both magnetization orientations as a function of the current in the wire computed by Eq. (64).

The effective anisotropy field decreases linearly as a function of the applied current. As the current density is increased from 3.7×10^{10} to $8.3 \times 10^{10} \text{ A/m}^2$, the anisotropy field reduces by $\sim 600 \text{ Oe}$ from 5.7 kOe to 5.1 kOe . Given that the effective anisotropy field is expressed as $H_K = 2K_{\perp} / M_S - 4\pi M_S$, we postulate that the current modulates the perpendicular anisotropy constant of the film stack. In general, the magnetic anisotropy constant can be varied by magnetic annealing effect, photo-induced magnetic anisotropy, crystallographic transformations or roll magnetic anisotropy [33]. In our experiment, the measurements were performed in a dark room at room temperature. As the Hall resistance was computed for each bias current value separately and the SOT effective fields scale linearly with current, the temperature effect due to Joule heating can be neglected here. Therefore this magnetic anisotropy decrease is due to SOT effects. Similar to the measurement conducted for the dampinglike field H_{DL} , the effective fieldlike field H_{FL} is computed by measuring the first and second harmonic Hall voltages while sweeping the external magnetic field along the y-axis. In Fig. 37 (a) the effective fieldlike field is shown as a function of the AC bias current density in the wire. As expected, the fieldlike field increases linearly as a function of the applied current [76, 25]. For a current density of $8.3 \times 10^{10} \text{ A/m}^2$ the fieldlike field

is computed to ~ 90 Oe for both orientations ($\pm z$) of magnetization. This value is 4 times smaller as compared to the measured effective fieldlike field, H_{FL} , using DW depinning from Fig. 34 (b). Harmonics measurement for quantifying the fieldlike field term is known to examine a lower values due to ignoring the contribution of the PHE symmetry in the measurement. The measured fieldlike field H_{FL} needs to be multiplied by a correcting factor which depends on the PHE to AHE ratio [61, 41]. The computation for the corrected fieldlike field is obtained from Ref. [167] as

$$H_{FL,PHEcorr} = \frac{H_{FL} + 2\zeta H_{DL}}{1 - 4\zeta^2}. \quad (65)$$

Assuming a PHE to AHE resistance ratio of 0.3 which is obtained from Ref. [99], the PHE corrected fieldlike field $H_{FL,PHEcorr}$ using the harmonic Hall measurement technique is computed to be ~ 400 Oe for a current density of 8.3×10^{10} A/m². This is in good agreement with our obtained result using DW depinning as a detection method, as can be seen in Fig. 37 where both computed fields are shown for +z-axis magnetization.

Figure 37: (a) Fieldlike effective field for both magnetization orientations as a function of the AC in the wire. (b) Comparison of the fieldlike effective fields obtained using depinning field and harmonic Hall voltage modulation with PHE correction as a function of current density.

The depinning field method using DWM is even underestimated which might indicate a lower PHE to AHE ratio or might be a result of subtraction to a reference value in the field determination using DWM. Interestingly, the corrected dampinglike effective field is found to be ~ 360 Oe for a current density of 8.3×10^{10} A/m², using the same PHE to AHE resistance ratio. This can be compared with previous results [167]. Thermoelectric effects such as anomalous Nernst effect and spin Seebeck effect might also add to the voltage signal, that influences the accuracy of the measurement [4].

3.6 SUMMARY

DW dynamics in a Pt/(Co/Ni)₄/Co/IrMn stack structure obtaining out-of-plane magnetic anisotropy and exchange bias has been investigated. Direct observation of magnetization switching *via* DWM has been shown using differential Kerr imaging microscopy technique. The AFM layer providing out-of-plane exchange bias does not influence the SOT fields determination. Field-driven DW depinning and motion is shown to be an alternative mean to quantifying the SOT effective field which is compared with conventional harmonic Hall voltage modulation technique to characterize SOT effective fields. By taking the PHE correction into consideration to quantifying SOT effective fields, both methods are in good agreement. Additionally, the bias current in the wire leads to a decrease in out-of-plane coercivity and effective magnetic anisotropy field, H_K , which can be attributed to SOT effective fields within the system. Our results cross-check the validity of the harmonic Hall voltage technique using a different method, which highlight the effectiveness of using harmonic Hall voltage technique in investigating SOT effective fields. Our results cross-check the validity of the harmonic Hall voltage technique using a different method, which highlight the effectiveness using harmonic Hall voltage technique in investigating SOT effective fields.

MAGNETIZATION ANGULAR DEPENDENCE OF SOT FIELDS

In this chapter, a detailed analytical derivation for the SOT effective fields determination with arbitrary in-plane magnetization angles is derived. The experimental evaluation is carried out for the BTO sample. This chapter has been reproduced from published article in **Physical Review B** [44].

4.1 MOTIVATION

A charge current in the HM/FM wire directed along the x-axis direction generates dampinglike torque $\vec{\tau}_{DL} = -H_{DL}\vec{M} \times (\hat{m} \times \hat{y})$ and fieldlike torque $\vec{\tau}_{FL} = -H_{FL}\vec{M} \times \hat{y}$ on the FM layer, where $\hat{y}$ describes the direction of electron spin from spin-polarized current to the local magnetization and $\hat{z}$ the direction of the surface normal [9, 142, 178, 177]. The torques are characterized by the corresponding effective fields as dampinglike field $\vec{H}_{DL} = H_{DL}\hat{m} \times \hat{y}$ and fieldlike field $\vec{H}_{FL} = H_{FL}\hat{y}$. These SOTs are believed to be generated from the bulk SHE [104, 91, 63, 102] in the HM material with strong SOI and the Rashba effect [104, 97, 129, 162] at the interface with strong interfacial SOC. Yet, the identification of the dominant term remains difficult as both SHE and Rashba effects generate both torques with same expression [93, 57, 2]. Fan et al. [48] managed to identify the contributions of the Rashba effect from interface effects by inserting a copper layer at the interface to minimize the Rashba effect and distinguish effects from Rashba and from SHE in Pt/CoFeB bilayers. However, the ratio between dampinglike and fieldlike torques has been detected to vary between ~ 1 [43] and up to ~ 8 [28], which shows a rather complicated behavior. Ta-thickness dependence study using harmonic Hall measurement technique in Ta/CoFeB/MgO structure with PMA suggests a sign change of the fieldlike torque at small thicknesses of Ta (<1.5 nm) which is also nontrivial [76]. Theoretical predictions based on Boltzmann transport equation and diffusion theory suggest two mechanisms with different dependencies on the thickness of the HM layer [2], but they also predict fieldlike and dampinglike torques are independent on the rotation of magnetization normal to the film plane [178]. Garello et al. [53] showed a strong angular dependence of SOT effective fields on the magnetization polar angle with respect to the current direction which cannot be explained by the Boltzmann theory. Another model based on the tight-binding theory predicts a strong angular dependence in SOTs with the Rashba spin-orbit cou-

pling being comparable to the exchange coupling strength [86]. The origin of current-induced SOTs in HM/FM structures with PMA is still under debate. Hence, angular dependence measurements of SOTs are a powerful tool to deeply understand the underlying physics in HM/FM structures and incorporating them into spin-orbit spintronics devices. Here, Co/Pt bilayers have been chosen for investigation as first-principle calculations predict both the spin-orbit potential and the exchange splitting being large near the interface of HM/FM [57]. The thermal stability and the PMA strength has been increased by repeating the Co/Pt layers [139]. BTO has been chosen as it obtains an intrinsic electric field which might provide additional features through an induced Rashba field at its interface. The BTO layer also caps the system from oxidation. A thin Ta layer capped the FM layer from oxidation while the material system was transferred for the BTO deposition.

4.2 ANALYTICAL DERIVATIONS

Sections 4.2.1 and 4.2.2 describe the derivations for the magnetization angle modulation and the Hall voltage modulation via external or current-induced magnetic fields to provide the reader a comprehensive understanding of the analytical model. Section 4.2.3 represents the actual work of the current-induced effective fields for arbitrary in-plane magnetization angles. For completion, section 4.2.4 provides information on the calculation of the SOT effective field errors.

4.2.1 Modulation of the magnetization angle by magnetic field

In this section, a description of the change in magnetization angle altered by an externally applied or current-induced field for a magnetic structure is derived.

Figure 38: Schematic of device structure and description of magnetization and applied field angles.

The magnetic energy in the system can be expressed as

$$E = -K_{Eff} \cos^2 \theta - K_I \sin^2 \varphi \sin^2 \theta - \vec{M} \bullet \vec{H}, \quad (66)$$

with K_{Eff} being the effective out-of-plane anisotropy constant and K_I being the effective in-plane anisotropy constant. The effective out-of-plane anisotropy constant is usually given for an ultrathin film wire as $K_{Eff} = K_U - \frac{1}{2}(N_Z - N_X)M_S^2$ with K_U the uniaxial magnetic anisotropy and the effective in-plane anisotropy constant as $K_I = \frac{1}{2}(N_X - N_Y)M_S^2$ [61]. M_S is the saturation magnetization of the vector $\vec{M}$ and N_X , N_Y and N_Z are the demagnetizing components of the demagnetizing tensor, as explained in section 1.1.4. θ and φ are polar and azimuthal angles of the magnetization as defined in Fig. 38. The vectors $\vec{M}$ and $\vec{H}$ are defined in Fig. 38 as follows:

$$\vec{M} = M_S \begin{pmatrix} \sin \theta \cos \varphi \\ \sin \theta \sin \varphi \\ \cos \theta \end{pmatrix} \quad (67)$$

$$\vec{H} = \begin{pmatrix} H_{X-ext} \\ H_{Y-ext} \\ H_{Z-ext} \end{pmatrix} = H \begin{pmatrix} \sin \theta_H \cos \varphi_H \\ \sin \theta_H \sin \varphi_H \\ \cos \theta_H \end{pmatrix}. \quad (68)$$

H_{X-ext} , H_{Y-ext} and H_{Z-ext} are the components of the applied field pointing along the respective axis direction. θ_H and φ_H are the polar and azimuthal angles of the applied field using spherical coordinates. An externally applied magnetic field, $\vec{H}$, changes the magnetic energy in the system according to Eq. 66. The magnetic energy reaches a new equilibrium after a relaxation time (usually in the order of nanoseconds). The magnetization angles in the new equilibrium position can be derived by the energy derivatives $\partial E / \partial \varphi = 0$ and $\partial E / \partial \theta = 0$. In the presented scenario, the out-of-plane component of the externally applied field is set to zero as $H_{Z-ext} = 0$ aligning the applied field in-plane. Inserting $\vec{M}$ and $\vec{H}$ in Eqs. (67, 68) into Eq. (66), the derivatives are given by

$$\begin{aligned} \frac{\partial E}{\partial \theta} = & -K_{Eff} \cos \theta \sin \theta - 2K_I \sin \theta \cos \theta \sin^2 \varphi \\ & - M_S H_{Y-ext} \cos \theta \sin \varphi - M_S H_{X-ext} \cos \theta \cos \varphi, \end{aligned} \quad (69)$$

$$\begin{aligned} \frac{\partial E}{\partial \varphi} = & -2K_I \sin^2 \theta \sin \varphi \cos \varphi \\ & - M_S H_{Y-ext} \sin \theta \cos \varphi + M_S H_{X-ext} \sin \theta \sin \varphi. \end{aligned} \quad (70)$$

Assuming $K_I \ll K_{Eff}$ which applies for samples with strong PMA, the in-plane anisotropy constant K_I can be neglected here. The effective out-of-plane anisotropy constant, K_{Eff} , can be substituted by an effective

anisotropy field by $H_K = 2K_{eff}/M_S$. In an equilibrium position, the derivatives can be set to zero which allows to derive the magnetization polar and azimuthal angle θ and φ . The polar angle and its derivative can be derived executing $\partial E/\partial\theta = 0$ as

$$\theta = \arcsin \left(\frac{H_{X-ext} \cos \varphi + H_{Y-ext} \sin \varphi}{H_K} \right), \quad (71)$$

$$\Delta\theta = \frac{\partial\theta}{\partial\vec{H}} \bullet \Delta\vec{H} \approx \frac{\Delta H_X \cos \varphi + \Delta H_Y \sin \varphi}{H_K}. \quad (72)$$

The azimuthal angle and its derivative then can be similarly derived executing $\partial E/\partial\varphi = 0$ as

$$\varphi = \arctan \left(\frac{H_{Y-ext}}{H_{X-ext}} \right), \quad (73)$$

$$\Delta\varphi = \frac{\partial\varphi}{\partial\vec{H}} \bullet \Delta\vec{H} = \frac{\Delta H_Y H_{X-ext} - \Delta H_X H_{Y-ext}}{H_{X-ext}^2 + H_{Y-ext}^2}. \quad (74)$$

The fractions $\partial\theta/\partial\vec{H}$ and $\partial\varphi/\partial\vec{H}$ represent the change in angles θ and φ through the current-induced effective field, $\Delta\vec{H}$.

4.2.2 Harmonic Hall voltage modulation via current

In this section, a description of the harmonic Hall voltages including current-induced effective fields is derived. For a magnetic wire, the transverse Hall voltage, V_H , typically contains contributions of the ordinary Hall effect (OHE), AHE, PHE and SMR which can be written as:

$$V_H = V_A + V_{P\&S} + V_O. \quad (75)$$

V_H is the total Hall voltage, V_A is the Hall voltage due to AHE, $V_{P\&S}$ is the Hall voltage due to PHE or SMR and V_O is the Hall voltage due to OHE. The contributions from the PHE and SMR to the Hall voltage have identical symmetry and as such cannot be distinguished. For external fields applied in-plane with negligible out-of-plane contributions to the wire structure, the OHE can be neglected. The Hall voltage can then be re-written [120, 130, 76, 163, 29] as

$$V_H = V_A + V_{P\&S} = \frac{1}{2} I \Delta R_A \cos \theta + \frac{1}{2} I \Delta R_{P\&S} \sin^2 \theta \sin 2\varphi. \quad (76)$$

ΔR_A represents the resistance through AHE and $\Delta R_{P\&S}$ represents the resistance through PHE or SMR. I stands for the constant current in the wire. As the Hall resistances are considered constant here, a change in Hall voltage represents a modulation of the magnetization vector. The modulation of the magnetization vector is described by its polar and azimuthal angles through an external field, Eqs. (71) and (73),

or by the current-induced effective fields, $\Delta\vec{H}$, which lead to small deviations of the magnetization vector by $\Delta\theta$, $\Delta\varphi$.

For an AC source in the magnetic wire, the current-induced harmonic modulation of the current and the magnetization angles can be written as:

$$\begin{aligned} I &\xrightarrow{ac} I_{ac} \sin \omega t \\ \varphi + \Delta\varphi &\xrightarrow{ac} \varphi + \Delta\varphi \sin \omega t \\ \theta + \Delta\theta &\xrightarrow{ac} \theta + \Delta\theta \sin \omega t \end{aligned}$$

The angular frequency $\omega = 2\pi f$ must be small with respect to the magnetization modulation frequency which is usually in the GHz range. The exchanges for an AC in the wire can be inserted into the Hall voltage, Eq. (76), which gives

$$V_A = \frac{1}{2} I_{ac} \sin \omega t \Delta R_A \cos(\theta + \Delta\theta \sin \omega t), \quad (77)$$

$$\begin{aligned} V_{P\&S} &= \frac{1}{2} I_{ac} \sin \omega t \Delta R_{P\&S} \sin^2(\theta + \Delta\theta \sin \omega t) \\ &\quad \sin(2(\varphi + \Delta\varphi \sin \omega t)). \end{aligned} \quad (78)$$

By exploiting small magnetization angle variations, Taylor expansion can be used as:

$$f(x + \delta) = f(x) + f'(x) \bullet \delta + f''(x) \bullet \frac{\delta^2}{2} + \gamma(x^3). \quad (79)$$

Here, we use first order of Taylor expansion for evaluating an expression for the respective Hall voltages. The Hall voltages, then, simplify to

$$V_A \approx \frac{1}{2} I_{ac} \sin \omega t \Delta R_A (\cos \theta - \Delta\theta \sin \theta \sin \omega t), \quad (80)$$

$$\begin{aligned} V_{P\&S} &\approx \frac{1}{2} I_{ac} \sin \omega t \Delta R_{P\&S} (\sin^2 \theta + 2\Delta\theta \sin \theta \cos \theta \sin \omega t) \\ &\quad (\sin 2\varphi + 2\Delta\varphi \cos 2\varphi \sin \omega t). \end{aligned} \quad (81)$$

We can now write the Hall voltage making use of the identity $\sin^2 \omega t = \frac{1}{2} - \frac{1}{2} \cos 2\omega t$ as

$$V_H = V_A + V_{P\&S} = V_0 + V_\omega \sin \omega t + V_{2\omega} \cos 2\omega t. \quad (82)$$

Inserting the Hall voltage into the harmonic voltage form, the constant voltage coefficient V_0 , the first harmonic Hall voltage V_ω and the second harmonic Hall voltage $V_{2\omega}$ can be written as

$$\begin{aligned} V_0 &= \frac{1}{2} I_{ac} \left(\frac{1}{2} [-\Delta R_A \sin \theta + \Delta R_{P\&S} \sin 2\theta \sin 2\varphi] \Delta\theta \right. \\ &\quad \left. + \Delta R_{P\&S} \sin^2 \theta \cos 2\varphi \Delta\varphi \right), \end{aligned} \quad (83)$$

$$V_\omega = \frac{1}{2}I_{ac}[\Delta R_A \cos \theta + \Delta R_{P\&S} \sin^2 \theta \sin 2\varphi], \quad (84)$$

$$V_{2\omega} = -\frac{1}{2}I_{ac}\left(\frac{1}{2}[-\Delta R_A \sin \theta + \Delta R_{P\&S} \sin 2\theta \sin 2\varphi]\Delta\theta + \Delta R_{P\&S} \sin^2 \theta \cos 2\varphi\Delta\varphi\right). \quad (85)$$

From Eqs. (71-74) it is obvious that the information of the current-induced effective fields, $\Delta\vec{H}$, is only noticeable in the second harmonic Hall voltage through the magnetization modulations $\Delta\theta$ and $\Delta\varphi$ in $V_{2\omega}$. In both harmonic Hall voltages, V_ω and $V_{2\omega}$, the information of H_K is provided.

4.2.3 Angular dependence of SOT effective fields

In this section, we insert the derived description of the magnetization angle modulation in section 4.2.1 into the Hall voltage description derived in section 4.2.2. A formula, then, is derived for the current-induced effective fields without taking simplification for the in-plane angle of the external field, φ_H , into consideration.

For PMA structures, the azimuthal angle can be set to $\varphi_H = \varphi$ which can be calculated from Eq. (73). Inserting the magnetization angles and angle modulations in Eqs. (71-74) and using the simplification for small angles ($\cos \theta = \sqrt{1 - \sin^2 \theta} \approx 1 - \frac{1}{2} \sin^2 \theta$) into the harmonic Hall voltages in Eqs. (84, 85) give

$$V_\omega \approx \left[\pm \frac{1}{2} \Delta R_A \left(1 - \frac{1}{2} \frac{H^2}{H_K^2} \right) + \frac{1}{2} \Delta R_{P\&S} \sin 2\varphi_H \frac{H^2}{H_K^2} \right] I_{ac}. \quad (86)$$

$$V_{2\omega} = \left[\frac{1}{4} [\pm \Delta R_A - 2\Delta R_{P\&S} \sin 2\varphi_H] (\Delta H_X \cos \varphi_H + \Delta H_Y \sin \varphi_H) - \frac{1}{2} \Delta R_{P\&S} \cos 2\varphi_H (\Delta H_Y \cos \varphi_H - \Delta H_X \sin \varphi_H) \right] \frac{H}{H_K^2} I_{ac}. \quad (87)$$

Here, the $\pm$ sign corresponds to the initial magnetization vector pointing along the $\pm z$ -axis direction. This is a consequence of the spherical coordinate system as the magnetization polar angles are θ for $+z$ magnetization orientation, $\pi - \theta$ for $-z$ orientation, and the magnetization polar angle variation is $\pm\Delta\theta$ for $\pm z$ magnetization orientation respectively. The information of the external applied field amplitude, H , can be removed by exploiting the derivatives of the harmonic Hall voltages with respect to H as

$$b_\omega = \frac{\partial^2 V_\omega}{\partial H^2} \approx -\frac{I_{ac}}{2H_K^2} \left[\pm \Delta R_A - 2\Delta R_{P\&S} \sin 2\varphi_H \right]. \quad (88)$$

$$b_{2\omega} = \frac{\partial V_{2\omega}}{\partial H} = \left[\frac{1}{4} [\pm \Delta R_A - 2\Delta R_{P\&S} \sin 2\varphi_H] (\Delta H_X \cos \varphi_H + \Delta H_Y \sin \varphi_H) - \frac{1}{2} \Delta R_{P\&S} \cos 2\varphi_H (\Delta H_Y \cos \varphi_H - \Delta H_X \sin \varphi_H) \right] \frac{I_{ac}}{H_K^2}. \quad (89)$$

As both expressions, b_ω and $b_{2\omega}$, contain the factor I_{ac}/H_K^2 , the dependency on the current I_{ac} and the anisotropy field H_K can be removed to exclude artifacts related to these observables. Dividing Equation (89) by (88) as $B_{\varphi_H} = b_{2\omega}/b_\omega$ give

$$B_{\varphi_H} = -\frac{1}{2} (\Delta H_Y \cos \varphi_H + \Delta H_X \sin \varphi_H) + \frac{\Delta R_{P\&S} \cos 2\varphi_H (\Delta H_Y \cos \varphi_H - \Delta H_X \sin \varphi_H)}{\pm \Delta R_A - 2\Delta R_{P\&S} \sin 2\varphi_H}. \quad (90)$$

Reformulating Eq. (90) in terms of the current-induced effective fields, $\Delta H_{X,Y}$, leads to

$$B_{\varphi_H} = \alpha \Delta H_Y + \beta \Delta H_X \quad (91)$$

where the coefficients α and β are given by

$$\alpha = -\frac{1}{2} \sin \varphi_H + \frac{\xi \cos 2\varphi_H}{\pm 1 - 2\xi \sin 2\varphi_H} \cos \varphi_H, \quad (92)$$

$$\beta = -\frac{1}{2} \cos \varphi_H - \frac{\xi \cos 2\varphi_H}{\pm 1 - 2\xi \sin 2\varphi_H} \sin \varphi_H, \quad (93)$$

Figure 39: Coefficients α and β for ξ ratios of (a) $\xi = 0$, (b) $\xi = 0.2$, (c) $\xi = 0.4$ and (d) $\xi = 0.6$.

ξ is the ratio of the two Hall resistances given by $\xi = \Delta R_{P\&S} / \Delta R_A$. The coefficients α and β are functions of the angle $\varphi_H (= \varphi)$ and the resistance ratio ξ . The coefficients α and β for various ξ ratios can be seen in Fig. 39. As B_{φ_H} can be obtained from the measurement for any arbitrary azimuthal angle φ_H , the two unknown independent variables, ΔH_X and ΔH_Y , cannot be determined directly. Hence, a second value $B_{\varphi'_H}$ at an angle φ'_H must be obtained from the measurement to derive both unknown variables.

For a $B_{\varphi'_H}$ with $B_{\varphi'_H} = \alpha' \Delta H_Y + \beta' \Delta H_X$, to determine the current-induced effective fields, the absolute value of the coefficients for two azimuthal angles must be equal as given by

$$|\alpha(\xi, \varphi_H)| = |\beta'(\xi, \varphi'_H)|, \quad (94)$$

$$|\beta(\xi, \varphi_H)| = |\alpha'(\xi, \varphi'_H)|. \quad (95)$$

In order to obtain the equality of the absolute values, we can make use of the following identities:

$$\sin \varphi_H = \cos(90^\circ - \varphi_H) = \sin(180^\circ - \varphi_H), \quad (96)$$

$$\cos \varphi_H = \sin(90^\circ - \varphi_H) = -\cos(180^\circ - \varphi_H). \quad (97)$$

Inserting the identities into the coefficients α and β , we can write

$$\begin{aligned} \alpha &= -\frac{1}{2} \sin \varphi_H + \frac{\xi \cos 2\varphi_H}{\pm 1 - 2\xi \sin 2\varphi_H} \cos \varphi_H \\ &= -\frac{1}{2} \cos(90^\circ - \varphi_H) \\ &\quad + \frac{-\xi \cos(180^\circ - 2\varphi_H)}{\pm 1 - 2\xi \sin(180^\circ - 2\varphi_H)} \sin(90^\circ - \varphi_H) \\ &= -\frac{1}{2} \cos \varphi'_H - \frac{\xi \cos 2\varphi'_H}{\pm 1 - 2\xi \sin 2\varphi'_H} \sin \varphi'_H = \beta'. \end{aligned} \quad (98)$$

In the last step, the angle $90^\circ - \varphi_H$ was substituted by φ'_H . Similarly, we can write for β ,

$$\begin{aligned} \beta &= -\frac{1}{2} \cos \varphi_H - \frac{\xi \cos 2\varphi_H}{\pm 1 - 2\xi \sin 2\varphi_H} \sin \varphi_H \\ &= -\frac{1}{2} \sin(90^\circ - \varphi_H) \\ &\quad + \frac{\xi \cos(180^\circ - 2\varphi_H)}{\pm 1 - 2\xi \sin(180^\circ - 2\varphi_H)} \cos(90^\circ - \varphi_H) \\ &= -\frac{1}{2} \sin \varphi'_H + \frac{\xi \cos 2\varphi'_H}{\pm 1 - 2\xi \sin 2\varphi'_H} \cos \varphi'_H = \alpha'. \end{aligned} \quad (99)$$

For $B_{\varphi'_H}$ we can now write

$$\begin{aligned} B_{\varphi'_H} &= \alpha' \Delta H_Y + \beta' \Delta H_X \\ &= \beta \Delta H_Y + \alpha \Delta H_X \\ &= B_{90^\circ - \varphi_H}. \end{aligned} \quad (100)$$

Making use of Eqs. (91) and (100), an expression for the current-induced effective fields can be computed to

$$\Delta H_X = \frac{\beta B_{\varphi_H} - \alpha B_{90^\circ - \varphi_H}}{\beta^2 - \alpha^2}, \quad (101)$$

$$\Delta H_Y = \frac{\alpha B_{\varphi_H} - \beta B_{90^\circ - \varphi_H}}{\alpha^2 - \beta^2}. \quad (102)$$

Eqs. (101, 102) provide a simple tool to evaluate current-induced effective fields for arbitrary in-plane magnetization angles. When the two angles are set to $\varphi_H = 0^\circ$ and $\varphi'_H = 90^\circ$, the form previously derived is obtained [61].

Exploiting a second symmetry of α and β , the current-induced effective fields can be computed using angles φ_H and $\varphi'_H = 270^\circ - \varphi_H$. Using the following identities

$$\sin \varphi_H = -\cos(270^\circ - \varphi_H) = \sin(540^\circ - \varphi_H), \quad (103)$$

$$\cos \varphi_H = -\sin(270^\circ - \varphi_H) = -\cos(540^\circ - \varphi_H), \quad (104)$$

the coefficients α and β can be re-written as

$$\begin{aligned} \alpha &= -\frac{1}{2} \sin \varphi_H + \frac{\xi \cos 2\varphi_H}{\pm 1 - 2\xi \sin 2\varphi_H} \cos \varphi_H \\ &= +\frac{1}{2} \cos(270^\circ - \varphi_H) \\ &\quad - \frac{-\xi \cos(540^\circ - 2\varphi_H)}{\pm 1 - 2\xi \sin(540^\circ - 2\varphi_H)} \sin(270^\circ - \varphi_H) \\ &= +\frac{1}{2} \cos \varphi'_H + \frac{\xi \cos 2\varphi'_H}{\pm 1 - 2\xi \sin 2\varphi'_H} \sin \varphi'_H = -\beta', \end{aligned} \quad (105)$$

$$\begin{aligned} \beta &= -\frac{1}{2} \cos \varphi_H - \frac{\xi \cos 2\varphi_H}{\pm 1 - 2\xi \sin 2\varphi_H} \sin \varphi_H \\ &= +\frac{1}{2} \sin(270^\circ - \varphi_H) \\ &\quad + \frac{-\xi \cos(540^\circ - 2\varphi_H)}{\pm 1 - 2\xi \sin(540^\circ - 2\varphi_H)} \cos(270^\circ - \varphi_H) \\ &= +\frac{1}{2} \sin \varphi'_H - \frac{\xi \cos 2\varphi'_H}{\pm 1 - 2\xi \sin 2\varphi'_H} \cos \varphi'_H = -\alpha'. \end{aligned} \quad (106)$$

The current-induced effective fields then can be computed as

$$\Delta H_X = \frac{\beta B_{\varphi_H} + \alpha B_{270^\circ - \varphi_H}}{\beta^2 - \alpha^2}, \quad (107)$$

$$\Delta H_Y = \frac{\alpha B_{\varphi_H} + \beta B_{270^\circ - \varphi_H}}{\alpha^2 - \beta^2}. \quad (108)$$

Therefore, the current-induced effective fields can be cross-checked using the same measurement data.

4.2.4 Calculation of SOT effective field errors

To estimate the errors which occur through an offset angle of the external field orientation with respect to the current direction on the current-induced effective fields, an error propagation for the effective fields error is provided. The fitting function to the harmonic voltages add an additional error in the order of 0.01 with respect to the value. The error propagation for functions α and β are given by

$$\Delta(\alpha) = \left(-0.5 \cos \varphi_H - \frac{2\zeta \cos \varphi_H \sin 2\varphi_H}{1 - 2\zeta \sin 2\varphi_H} + \frac{4\zeta^2 \cos \varphi_H \cos^2 2\varphi_H}{(1 - 2\zeta \sin 2\varphi_H)^2} - \frac{\zeta \sin \varphi_H \cos 2\varphi_H}{1 - 2\zeta \sin 2\varphi_H} \right) \Delta(\varphi_H), \quad (109)$$

$$\Delta(\beta) = \left(0.5 \sin \varphi_H + \frac{2\zeta \sin \varphi_H \sin 2\varphi_H}{1 - 2\zeta \sin 2\varphi_H} - \frac{4\zeta^2 \sin \varphi_H \cos^2 2\varphi_H}{(1 - 2\zeta \sin 2\varphi_H)^2} - \frac{\zeta \cos \varphi_H \cos 2\varphi_H}{1 - 2\zeta \sin 2\varphi_H} \right) \Delta(\varphi_H). \quad (110)$$

As the coefficients α and β are functions of the same variables ζ and φ_H , the calculated error here is an overestimate of the real error. The error propagation due to $\Delta(\alpha)$ and $\Delta(\beta)$ are shown in Fig. 40. The current-induced effective field uncertainties can be computed as

$$\Delta(\Delta H_X) = \frac{\partial \Delta H_X}{\partial \alpha} \Delta(\alpha) + \frac{\partial \Delta H_X}{\partial \beta} \Delta(\beta), \quad (111)$$

$$\Delta(\Delta H_Y) = \frac{\partial \Delta H_Y}{\partial \alpha} \Delta(\alpha) + \frac{\partial \Delta H_Y}{\partial \beta} \Delta(\beta). \quad (112)$$

The derivatives for angles φ_H and $270^\circ - \varphi_H'$ are given by

$$\frac{\partial \Delta H_X}{\partial \alpha} = \frac{B_{270^\circ - \varphi_H}(\beta^2 - \alpha^2) - (\beta B_{\varphi_H} + \alpha B_{270^\circ - \varphi_H})(-2\alpha)}{(\beta^2 - \alpha^2)^2} \quad (113)$$

$$\frac{\partial \Delta H_X}{\partial \beta} = \frac{B_{\varphi_H}(\beta^2 - \alpha^2) - (\beta B_{\varphi_H} + \alpha B_{270^\circ - \varphi_H})(2\beta)}{(\beta^2 - \alpha^2)^2} \quad (114)$$

$$\frac{\partial \Delta H_Y}{\partial \alpha} = \frac{B_{\varphi_H}(\alpha^2 - \beta^2) - (\alpha B_{\varphi_H} + \beta B_{270^\circ - \varphi_H})(2\alpha)}{(\alpha^2 - \beta^2)^2} \quad (115)$$

$$\frac{\partial \Delta H_Y}{\partial \beta} = \frac{B_{270^\circ - \varphi_H}(\alpha^2 - \beta^2) - (\alpha B_{\varphi_H} + \beta B_{270^\circ - \varphi_H})(-2\beta)}{(\alpha^2 - \beta^2)^2} \quad (116)$$

The error bars in this thesis are calculated using an uncertainty of 0.5° for $\Delta(\varphi_H)$ as the minimum distance at the scale is 1° .

Figure 40: Error propagation of $\Delta(\alpha)$ and $\Delta(\beta)$ for (a) $\xi = 0$, (b) $\xi = 0.2$, (c) $\xi = 0.4$ and (d) $\xi = 0.6$ through an azimuthal angle offset of $\Delta(\varphi_H) = 0.5^\circ$.

4.3 EXPERIMENTAL DETAILS

To investigate the angular dependence of the **SOT** effective fields, a multilayer stack structure with **PMA** were fabricated and measured, namely **BTO** sample. The **BTO** reference sample comprises of stack structure Ta (5)/Pt (3)/Co (0.9)/Pt (1)/Co (0.9)/Ta (1) which was grown at room temperature on Si/SiO₂(300 nm) substrate using **DC** magnetron sputtering deposition technique. The numbers in brackets correspond to the respective film thicknesses in nm. The magnetization hysteresis loop for the **BTO** sample as obtained using Magneto optical Kerr setup reveals that the continuous film has an intrinsic **PMA** with a coercivity of 200 Oe acting as a single **FM** layer.

For the **BTO** sample a 10 nm **BTO** layer was subsequently deposited using **RF** magnetron sputtering technique. Prior to the **BTO** layer growth, the **BTO** reference stack was twice reverse sputtered in Ar plasma for 30 s to remove any naturally oxidization of the top Ta layer. No field or heat treatment to both samples was carried out. The **BTO** sample was patterned into Hall cross structure using a combination electron beam lithography and argon ion milling techniques. The Hall cross structure comprises of a 6 μm -wide current channel with Hall

bars. The length of the current channel and the Hall bars are 40 μm . A Keithley 6221 AC current source and a 7265 Dual Phase DSP lock-in amplifier were used for harmonic Hall voltage measurement. The AC frequency was set to 309 Hz at room temperature for all our measurements which ensures an adiabatical change of magnetization vector which is usually in the GHz range [44].

4.4 DETERMINATION OF ζ RATIO FOR THE BTO SAMPLE

The ratio of the PHE&SMR (P&S) resistance to AHE resistance, $\zeta = \Delta R_{P\&S} / \Delta R_A$, is an intrinsic material property and knowledge of the ratio is crucial for evaluating the coefficients α and β . Due to limitations in our experimental setup in applying large fields to saturate the magnetization of the PMA wire in-plane, a technique is devised for determining the P&S resistance using low external fields ($H \ll H_K$). From Eq. (76), the maximum and minimum values for R_H due to PHE or SMR would occur when the azimuthal angle is set to $+45^\circ$ and -45° respectively. The AHE resistance is measured to be $\approx 0.673 \Omega$ with an I_{ac} current in the wire of $1 \times 10^{11} \text{ A/m}^2$. Normalizing the Hall resistance R_H in terms of the AHE resistance ΔR_A results in

$$\tilde{R}_H = \frac{R_H}{\Delta R_A} = \frac{1}{2} \cos \theta + \frac{1}{2} \zeta \sin^2 \theta \sin 2\varphi. \quad (117)$$

Summing or subtracting $\tilde{R}_H$ measured at azimuthal angles of $+45^\circ$ and -45° leads to the following expressions which separates both terms in $\tilde{R}_H$:

$$\Delta \tilde{R}_H^+ = \tilde{R}_H^{+45^\circ} + \tilde{R}_H^{-45^\circ} = \cos \theta, \quad (118)$$

$$\Delta \tilde{R}_H^- = \tilde{R}_H^{+45^\circ} - \tilde{R}_H^{-45^\circ} = \zeta \sin^2 \theta = \zeta [1 - (\Delta \tilde{R}_H^+)^2]. \quad (119)$$

Shown in Fig. 41 (a) are the Hall resistance curves for sample with magnetization set along +z-axis orientation as the external field is swept at azimuthal angles of $\pm 45^\circ$. From Equation (119) the difference between the two curves in Fig. 41 (a), $\Delta \tilde{R}_H^-$, is calculated and plotted as a function of $[1 - (\Delta \tilde{R}_H^+)^2]$, as seen in Fig. 41 (b). A linear relation is observed and the gradient of the slope gives the term ζ . For our sample structure, the ratio is calculated to be $\zeta = 0.205 \pm 0.001$.

Figure 41: (a) Hall resistance as a function of applied field with azimuthal $\pm 45^\circ$ for the BTO sample. The polar angle θ_H is set to $\pi/2$. The subtracted normalized resistance $\Delta\tilde{R}_H^-$ as a function of $[1 - (\Delta\tilde{R}_H^+)^2]$ and linear fit to the data points are shown in (b).

The ratio ξ can be cross-checked by an alternative method by comparing the parabolic coefficients from the first harmonic Hall voltage, Eq. (84), directly. The parameter $b_\omega = \partial^2 V_\omega / \partial H^2$ can be extracted by a parabolic fit of the measured data points of the first harmonic Hall voltage as a function of the externally applied field, with the externally applied field directed at angles $\pm 45^\circ$ with respect to the current direction. The fitting parameters at applied fields with azimuthal angle $\pm 45^\circ$ can be read as

$$b_\omega^{\pm 45^\circ} = \frac{\partial^2 V_\omega}{\partial H^2 (\varphi_H = \pm 45^\circ)} = -\frac{\Delta R_A}{2H_K} \left(1 \mp 2 \frac{\Delta R_{P\&S}}{\Delta R_A} \right) I_{ac}. \quad (120)$$

An expression for the ratio ξ without prior knowledge of the anomalous Hall resistance ΔR_A is derived as

$$\xi = \frac{1}{2} \frac{(b_\omega^{-45^\circ} - b_\omega^{+45^\circ})}{(b_\omega^{-45^\circ} + b_\omega^{+45^\circ})}. \quad (121)$$

This value is obtained to $\xi = 0.203 \pm 0.001$. For all subsequent computations in our experiment, a value of $\xi = 0.204$ is used. This value is obtained from averaging ξ computed by both methods.

4.5 SPIN-ORBIT TORQUE EFFECTIVE FIELDS AS A FUNCTION OF CURRENT

To evaluate the [SOT](#) effective fields, first and second harmonic Hall voltages are measured as a function of external in-plane magnetic field for two cases; external field applied along the current direction (x-axis direction) and applied along the direction transverse to the current (y-axis direction). The externally applied field is swept in the range of ± 1.9 kOe to increase the [SNR](#). Hall voltages for sample magnetized

along $\pm z$ orientation is shown in Fig. 42. If the applied field is swept along the x- or y-axis, Eqs. (84) and (85) simplify to

$$V_\omega = \pm \frac{1}{2} \Delta R_A I_{ac} \mp \frac{1}{2} \frac{H^2}{H_K^2} \Delta R_A I_{ac} \text{ for x-, y-axis direction,} \quad (122)$$

$$V_{2\omega} = \left(\pm \frac{1}{4} \Delta R_A \Delta H_X - \frac{1}{2} \Delta R_{P\&S} \Delta H_Y \right) \frac{H}{H_K^2} I_{ac} \text{ for x-axis,} \quad (123)$$

$$V_{2\omega} = \left(\pm \frac{1}{4} \Delta R_A \Delta H_Y - \frac{1}{2} \Delta R_{P\&S} \Delta H_X \right) \frac{H}{H_K^2} I_{ac} \text{ for y-axis.} \quad (124)$$

Fig. 42 (a) and (b) show first harmonic Hall voltages for externally applied fields swept along x-axis direction (a) and along y-axis direction (b) at a constant current density of 1×10^{11} A/m² in the wire. Figures 42 (a) and (b) exhibit identical curves, as expected from Eq. (122). The second harmonic Hall voltages for externally applied fields swept along x-axis and y-axis directions are shown in Fig. 42 (c) and (d). The second harmonic Hall voltages exhibit linear relationships with external field which is consistent with Eqs. (123) and (124). As seen in Fig. 42 (c), identical slopes with an offset voltage at zero applied field of $\Delta V_{2\omega} \approx 0.3$ μ V are obtained for magnetization orientations with opposite out-of-plane sign, $\pm z$ orientation. The identical slope in Fig. 42 (c) corresponds to a constant coefficient in Eq. (123) as the magnetization is reversed, which give $+\frac{1}{4} \Delta R_A \Delta H_X - \frac{1}{2} \Delta R_{P\&S} \Delta H_Y = -\frac{1}{4} \Delta R_A \Delta H_X - \frac{1}{2} \Delta R_{P\&S} \Delta H_Y$. This implies a constant SOT effective field in y-axis direction (ΔH_Y) and an SOT effective field with opposite x-axis direction (ΔH_X), as the magnetization orientation is changed. This is consistent with the SOT effective field description in y-axis direction of the fieldlike term ($\vec{H}_{FL} = H_{FL} \hat{y}$) and in x-axis direction of the dampinglike term ($\vec{H}_{DL} = H_{DL} \hat{m} \times \hat{y}$).

Figure 42: (a), (b) first harmonic Hall voltage as a function of the applied in-plane field for the BTO sample. (a) shows the Hall voltage with field pointing along x-axis direction and (b) with field pointing along y-axis direction. (c), (d) second harmonic Hall voltage as a function of the applied in-plane field. (c) shows the Hall voltage with field pointing along x-axis direction and (d) with field pointing along y-axis direction. The black points correspond to a sample magnetized +z-axis orientation and the red points correspond to a sample magnetized in -z-axis orientation.

In Fig. 42 (d) is shown the second harmonic Hall voltage as the external field is applied along the y-axis direction. The magnitude of slopes for sample with opposite magnetization orientation are identical but exhibit a sign change. This implies from Eq. (124) a sign change of the coefficient, which give $+\frac{1}{4}\Delta R_A\Delta H_Y - \frac{1}{2}\Delta R_{P\&S}\Delta H_X = -(-\frac{1}{4}\Delta R_A\Delta H_Y - \frac{1}{2}\Delta R_{P\&S}\Delta H_X)$. This is consistent with a constant SOT effective field in y-axis direction ($\Delta\vec{H}_Y = \vec{H}_{FL}$) and an SOT effective field with opposite x-direction ($\Delta\vec{H}_X = \vec{H}_{DL}$). The same offset voltage at zero applied field of $\Delta V_{2\omega} \approx 0.3 \mu\text{V}$ is observed.

From first and second harmonic Hall voltages, the SOT effective fields can be computed using Equations (101) and (102) for external fields applied along x-axis direction ($\varphi_H = 0^\circ$) and y-axis direction ($\varphi_H = 90^\circ$). Equations (101) and (102) using annotations for the ratios $B_{\varphi_H=0^\circ} = B_X$ and $B_{\varphi_H=90^\circ} = B_Y$ simplify to

$$\Delta H_X = -2 \frac{(B_X \pm 2\tilde{\zeta}B_Y)}{1 - 4\tilde{\zeta}^2}, \quad (125)$$

$$\Delta H_Y = -2 \frac{(B_Y \pm 2\tilde{\zeta}B_X)}{1 - 4\tilde{\zeta}^2}. \quad (126)$$

As expected, Eqs. (125) and (126) reduce to a form consistent with that derived by Hayashi et al. [61], where no angular dependent term is present. The respective SOT effective fields obtained using Eqs. (125) and (126) as a function of current density are shown in Fig. 43.

Figure 43: Effective dampinglike field as a function of applied current density in the wire for BTO sample magnetized along +z orientation. (b) Effective fieldlike field and calculated Oersted field as a function of current density for BTO sample magnetized along +z orientation. The Oersted field was calculated from currents flowing in the non-magnetic channels.

As seen in Fig. 43 (a), the effective dampinglike field as a function of current density in the wire shows linear behavior. The effective dampinglike field is obtained to $\sim \pm 17.4$ Oe / (10^{11} A/m²) for $\pm z$ orientation of the magnetization. In Fig. 43 (b) the effective fieldlike field shows linear behavior at larger current densities with identical slopes for $\pm z$ orientations of the magnetization. At low current densities, a large SNR is responsible for the small uncertainty of the fieldlike term. The effective fieldlike field is found to ~ 8.4 Oe / (10^{11} A/m²) for both magnetization orientations. The Oersted field from the Ta/Pt sublayer as well as the Ta top layer is computed according to Hayashi et al. [61] which also scales linearly. The Oersted field assumed to originate mainly from the Ta/Pt sublayers, is directed along the negative y-axis direction. The Oersted field corrected effective fieldlike field is obtained to 12.7 Oe / (10^{11} A/m²). In a study using a Ta (4)/Pt (3)/Co (0.9)/Ta(1) stack material a dampinglike term of ~ 80 Oe / (10^{11} A/m²) and a fieldlike term of ~ 50 Oe / (10^{11} A/m²) is reported [61]. The increase of almost 5 times might be related to our double ferromagnetic layers and a 1.5 nm layer of TaO_x cap used in the reported study. The ratio ξ in our sample is 0.204 whereas in the reported study the ratio is ~ 0.34 , which is significantly larger and might be related to the larger SOT effective fields reported. The ratio $\Delta H_x / \Delta H_y$ is ~ 1.4 for our sample and ~ 1.6 for the sample reported.

4.6 ANGULAR DEPENDENCE OF SOT EFFECTIVE FIELDS IN BTO SAMPLE

Figure 44: Angular dependence of (a) $b_{2\omega}$, (b) b_{ω} , (c) B_{ϕ_H} with fit according to Eq. (91) and (d) the residual of the B_{ϕ_H} -fit for BTO sample. The AC bias current density in the wire was set to 1×10^{11} A/m².

To evaluate SOT effective fields as a function of the azimuthal angle, $\phi_H = \varphi$, with respect to the current direction in PMA structures, first and second harmonic Hall voltages (V_{ω} and $V_{2\omega}$) are measured as a function of the external applied field with magnetization direction of the FM wire set along the +z orientation for all measurements. The current density is set to 1×10^{11} A/m² in the wire to increase the SNR and the azimuthal angle ϕ_H is varied in 5° steps. For each field sweep at respective azimuthal angle, the first harmonic Hall voltage is fitted by a parabolic function to obtain the second derivative in H , $b_{\omega} = \partial^2 V_{\omega} / \partial H^2$, and the second harmonic Hall voltage is fitted by a linear function to obtain the first derivative in H , $b_{2\omega} = \partial V_{2\omega} / \partial H$. The fitting parameters b_{ω} and $b_{2\omega}$ as a function of the azimuthal angle ϕ_H are shown in Fig. 44 (a) and (b) respectively. As seen in Fig. 44 (a), the parameter $b_{2\omega}$ exhibits a predominantly $\cos \phi_H$ trend. In Figure 44 (b) the parameter b_{ω} exhibits a clear $\sin 2\phi_H$ behavior which is expected from Eq. (84). To remove the dependencies of the current and anisotropy field, the ratio $B_{\phi_H} = b_{2\omega} / b_{\omega}$ is computed, as shown in Fig. 44 (c). Assuming the SOT effective fields are constant with azimuthal angle ϕ_H , the ratio B_{ϕ_H} can be directly fitted using Eq. (90) and a ratio of $\zeta = 0.204$ to evaluate mean values for SOT effective fields, as seen

in Fig. 44 (c). The mean values for the SOT effective fields from the fitting function in Fig. 44 (c) are determined as 8.4 Oe / (10^{11} A/m²) for the fieldlike field and 17.0 Oe / (10^{11} A/m²) for the dampinglike field. This is consistent with the SOT effective fields computed in the section 4.5. The residual of the B_{φ_H} -fitting function is shown in Fig. 44 (d) which shows the scattering of the data points around the fitting function. In case both SOT fields are constant with azimuthal angle, the data points should be scattered randomly around the fit, which is not the case. As such, an angular dependence of at least one term of the SOT effective fields can be expected.

Figure 45: Computed SOT effective fields for the BTO sample as a function of azimuthal angle φ_H of the applied field with respect to current direction. The current density was 1×10^{11} A/m² for all measurements. (a) Dampinglike effective field according to Eq. (101). (b) Dampinglike effective field according to Eq. (107). (c) Fieldlike effective field according to Eq. (102). (d) Fieldlike effective field according to Eq. (108). The dashed lines are the symmetry axes.

To evaluate the dependency of the SOT effective fields on the azimuthal angle, the SOT effective fields are computed from B_{φ_H} using Eqs. (101, 102) and (107, 108) from the section 4.2, as seen in Fig. 45. Both SOT effective fields can be cross-checked by using different symmetry axes with the same measured data points. The symmetry axes are indicated as red dashed lines in Fig. 45. At symmetry axes where $\alpha^2 = \beta^2$, no effective field can be computed. At angles, φ_H , close to the symmetry axes, the computation delivers larger errors whereas

small errors are obtained between symmetry axes. The mean value for the dampinglike field is found to $\sim 17.1 \text{ Oe} / (10^{11} \text{ A/m}^2)$ which is similar to the value obtained from angles 0° and 90° . Comparing Fig. 45 (a) with 45 (b), we obtain similar relations with two minima at azimuthal angles of 45° and 225° . This provides a clear indication of azimuthal angular dependence of the dampinglike effective field in the Pt/Co/Pt/Co/Ta/BTO heterostructure. The mean value of the fieldlike field is found to $\sim 8.8 \text{ Oe} / (10^{11} \text{ A/m}^2)$ which is also similar to the value obtained at 0° and 90° . Comparing Fig. 45 (c) with (d) for the fieldlike field, no such relation is observed.

The lack of angular dependency for the fieldlike term may be attributed to the smaller ratio of the Rashba spin-orbit coupling to the exchange coupling of the magnetic material or competing effects with opposite sign. As predicted by Lee et al. [86], when the Rashba spin-orbit coupling is larger than the exchange coupling, an angular dependency of the SOT terms might arise.

4.7 SUMMARY

In this chapter, we have developed and experimentally tested a harmonic Hall technique to quantify SOT effective fields as a function of the magnetization azimuthal angle with respect to the current direction in PMA structures. Based on the energy balance equation, analytical solutions are provided to extract the SOT effective fields from first and second harmonic Hall voltages measured at two different azimuthal angles of the external field. Two methods to quantify the ratio of two different symmetries in Hall voltages originated from AHE on one side and from PHE and SMR on the other side are provided for low external magnetic field sweeps. Experimental study was carried out on Pt/Co/Pt/Co/Ta/BTO sample exhibiting strong PMA. The ratio of the AHE resistance to PHE&SMR resistance has been found to 0.204 for the BTO sample. The average dampinglike term for the BTO sample is found to be $\sim 17.4 \text{ Oe}$ per $1 \times 10^{11} \text{ A/m}^2$ and the average fieldlike term to be $\sim 12.7 \text{ Oe}$ per $1 \times 10^{11} \text{ A/m}^2$ corrected by computed Oersted field of $\sim 4.3 \text{ Oe}$ per $1 \times 10^{11} \text{ A/m}^2$. An angular dependence of the dampinglike term is found for the BTO sample with minima at 45° and 225° corresponding to a $-\sin 2\varphi$ -symmetry. The fieldlike term for the BTO sample shows negligible angular dependence. Our presented model provides a new platform for future studies characterizing SOT effective fields on the magnetization direction in PMA structures.

SYMMETRY CHARACTERIZATION OF ANGULAR DEPENDENT SOT FIELDS

In this chapter, various properties are investigated for angular dependence of SOT fields in Pt/(Co/Ni)₂/Co/Ta heterostructure. Fourier analysis characterizes different symmetry behavior of the SOT field angular dependence. Anisotropy and a newly introduced in-plane field offset are also described by means of angular dependence measurement.

5.1 MOTIVATION

The understanding of SOT in FM heterostructures has been limited so far as in nominally identical structures different magnitudes of SOT effective fields have been characterized. These discrepancies have been attributed to grain size and inter-diffusion of electrons in the ultrathin layers [93, 153]. One key tool to expose the underlying physics is by measuring the angular dependence of these SOT effective fields. While the Boltzmann transport equation postulates that no angular dependence on the magnetization of the dampinglike torque and fieldlike torque is expected [178], several investigations have reported a large angular dependence of the SOTs on the magnetization polar angle [53, 131, 28]. Lee et al. theoretically predicted the angular dependence of SOTs based on free electron and tight-binding theories which might provide more insight on the underlying physics causing SOT [86]. The angular dependence of SOT fields is notably when a certain ratio of the Rashba SOC parameter with respect to the exchange interaction parameter is fulfilled. Sakanashi et al. [136] used a semiclassical approach incorporating spin diffusion equation for the SHE and NM [176, 29, 119], the quantum Boltzmann approach for interface Rashba SOC [97] and quantum tunneling theory for SHE-induced spin injection mediated by quantum well state [119, 26, 27]. However, the derived polar angular dependence of SOT fields yet does not match with the polar angular dependence reported in experimental studies [53, 131]. The azimuthal angular dependence of the SOT has been neglected so far as being considered weakly dependent [53, 54]. Here, two different PMA systems using a Co/Ni double stack and HMs Pt and Ta with two different thicknesses of the HM Ta are investigated. The Co/Ni double stack enhances the PMA strength in the system due to a larger thickness. The different Ta thicknesses influence the SOT magnitude and other magnetic material properties in the heterostructure, which can be compared [41, 53, 93, 34, 167, 107, 137, 175, 123]

5.2 EXPERIMENTAL DETAILS

To investigate symmetry aspects of the angular dependence of the SOT effective fields, two multilayer stack structures with same lateral Hall structure of $10\ \mu\text{m}$ wide magnetic Hall bar and magnetic wire with each $70\ \mu\text{m}$ in length have been fabricated. Both Ta samples comprise of stack structure Ta (5)/Pt (5)/[Co (0.3)/Ni (0.5)]₂/Co (0.3)/Ta (x) grown at room temperature on Si/SiO₂(300 nm) substrates using DC magnetron sputtering deposition technique. The numbers in brackets correspond to the respective film thicknesses in nm where the capping Ta layer exhibit $x=1.2$ and $x=2.4$ nm which is also used here as a label for the respective sample as Ta 1.2 and Ta 2.4 nm. The samples were patterned into Hall cross structures as described in section 2.1.2. From R_H - H_Z hysteresis loop measurements of Ta 1.2 nm and Ta 2.4 nm sample, a coercivity of ~ 210 Oe for the Ta 1.2 nm and of ~ 65 Oe for the Ta 2.4 nm sample were obtained. All electrical measurements were conducted at room temperature and the AC frequency of the sense current was set to 309 Hz. The same description is used as shown in the schematic of Fig. 38 in the section 4.2.1.

5.3 FOURIER ANALYSIS OF ANGULAR DEPENDENT SOT FIELDS

Figure 46: Angular dependence of b_ω , $b_{2\omega}$ and B_{ϕ_H} for Ta 1.2 nm and Ta 2.4 nm sample. (a), (c) and (e) show the parameters b_ω , $b_{2\omega}$ and B_{ϕ_H} for the Ta 1.2 nm sample and (b), (d) and (f) show the parameters b_ω , $b_{2\omega}$ and B_{ϕ_H} for the Ta 2.4 nm sample respectively. The current density was set to 2×10^{10} A/m².

To obtain SOT effective fields as a function of the azimuthal angle, first and second harmonic Hall voltages are measured at various azimuthal angles, $\phi_H = \phi$, with respect to current direction. The current density was kept constant at 2×10^{10} A/m² and the azimuthal angle was varied in 5° steps. In Fig. 46 (a) and 46 (b) the derivative b_ω is shown for sample with Ta 1.2 nm (a) and with Ta 2.4 nm (b). As expected, a clear $\sin 2\phi_H$ trend is observed in both graphs originating from the PHE and SMR. Interestingly, the amplitude of b_ω has nearly

doubled for Ta 2.4 nm sample as compared to the sample of Ta 1.2 nm thickness capping. Similarly, the derivative $b_{2\omega}$ is shown in Fig. 46 (c) for Ta 1.2 nm sample and in Fig. 46 (d) for Ta 2.4 nm sample. A $\cos(\varphi_H - \delta)$ trend is observed for both graphs. This is in line with the second harmonic Hall voltage being a combination of cosine and sine functions depending on the respective ratios of PHE, SMR to AHE resistances and both effective fields to each other. The amplitude of $b_{2\omega}$ is, again, around twice for Ta 2.4 nm as compared to $b_{2\omega}$ for Ta 1.2 nm. It should be noted that a larger offset angle δ usually indicates a larger ratio of ζ . This is even more profound in Figs. 46 (e) and 46 (f) where the ratio B_{φ_H} is shown for Ta 1.2 nm in Fig. 46 (e) and for Ta 2.4 nm in Fig. 46 (f). The ζ ratio for the shape in Fig. 46 (f) was determined to ~ 0.40 whereas the ζ ratio for shape in Fig. 46 (e) was determined to ~ 0.48 which indicates rounder curves for lower ζ values. The ratio B_{φ_H} can be fitted by using Eq. (91). From the fits in Fig. 46 (e) and 46 (f) with prior knowledge of α and β , the average values for SOT effective fields can be extracted as coefficients from the fits. For Ta 1.2 nm sample, the dampinglike field was obtained by 34.5 ± 0.8 Oe and the fieldlike field including Oersted field by 27.2 ± 0.9 Oe. For Ta 2.4 nm sample, the dampinglike field was obtained by 18.0 ± 0.2 Oe and the fieldlike field including Oersted field by 10.2 ± 0.2 Oe. The ratios, $\Delta H_X / \Delta H_Y$, are obtained by ~ 1.27 for Ta 1.2 nm sample and by ~ 1.76 for Ta 2.4 nm sample. However, the difference of the SOT effective fields, $\Delta H_X - \Delta H_Y$, are close with ~ 7.3 Oe for Ta 2.4 nm sample and ~ 7.8 Oe for Ta 1.2 nm sample. This might provide a different view about the mechanism of the SOT effective fields, which are usually employed to evaluate by their respective ratios.

Figure 47: (a) and (b) show SOT effective fields of Ta 1.2 nm and Ta 2.4 nm sample. (c) and (d) show the Fourier analysis of the angular dependent dampinglike field for Ta 1.2 nm and Ta 2.4 nm sample. (e) and (f) show the Fourier analysis of the angular dependent fieldlike field for Ta 1.2 nm and Ta 2.4 nm sample. The current density was set to 2×10^{10} A/m².

The SOT effective fields can be directly computed from the respective B_ϕ values as described in section 4.2.3 by Eqs. (101), (102), (107) and (108). The computed SOT effective fields are shown in Fig. 47. For simplicity, the SOT effective fields are averaged as $\Delta H_{X,Y} = [\Delta H_{X,Y}(\phi_H, 90^\circ - \phi_H) + \Delta H_{X,Y}(\phi_H, 270^\circ - \phi_H)]/2$. As seen in Fig. 47 (a), large angular dependence of both SOT effective fields on the azimuthal angle are observed. Two maxima at angles of 135° and 315° with minima between are visible. Interestingly, both effective fields seem to have the same behavior with azimuthal angle with a nearly

constant offset field of ~ 8 Oe between the dampinglike field and the fieldlike field. Similar trends with lower magnitude of angular dependence are observed in Fig. 47 (b) for Ta 2.4 nm sample. This is a clear indication, that the azimuthal angle dependence of SOT effective fields as well as the PHE&SMR correction cannot be neglected which is for our samples ($\zeta > 0.4$) quite significant.

To evaluate the symmetry of the azimuthal angular dependence, Fourier series was performed which decomposes any periodic symmetry into a set of orthogonal sine and cosine functions representing the periodic signal. 4th order was chosen as a representation of symmetries each 90° which can be expected by a 360° rotation. The fitting function for the Fourier series is given by

$$f(x) = A + \sum_{n=1}^4 [B_n \sin(nx) + C_n \cos(nx)]. \quad (127)$$

The Fourier series fits can be seen in Figs. 47 (c)-(f). The respective coefficients are listed in Table 1. The constant offset A is larger for all effective fields as compared to the previous computation of the effective fields using the fit for B_{ϕ_H} . The two obvious maxima (peaks) at angles of 135° and 315° are well approximated by large negative coefficients of B_2 , which describe a $-\sin 2\phi$ relationship. For Ta 1.2 nm sample, the coefficients for both effective fields are nearly identical at -11.1 Oe and -11.5 Oe. For Ta 2.4 nm sample, the coefficients are read to -1.79 Oe and -1.90 Oe for the dampinglike and the fieldlike terms respectively. The significantly larger values for the coefficient B_2 of the Ta 1.2 nm sample might be related to the notably larger difference of A to the previous obtained SOT effective field for Ta 1.2 nm sample (43.2 Oe - 34.5 Oe ≈ 8.7 Oe) as compared to the Ta 2.4 nm sample, whose value of A increased by ~ 1.2 Oe. Further relationships for Ta 1.2 nm sample can be detected by B_3 , C_1 and C_4 which are twice the error values and therefore considered detectable. For Ta 2.4 nm sample, B_1 , C_1 and C_4 are larger as compared to their error values. For C_3 the value for fieldlike term is remarkably larger as its error value, however the dampinglike term is lower as compared to its error value. This makes it difficult to evaluate an angular dependence for this specific symmetry. Considering symmetries which should appear in both samples, the coefficients B_2 , C_1 and C_4 show noticeable relationships in all evaluated effective fields. As for the B_2 coefficient, the fieldlike contribution is slightly larger as the dampinglike contribution. For the C_1 coefficient the contribution is nearly identical. For the C_4 coefficient, the dampinglike magnitude is slightly larger in the Ta 1.2 nm sample as compared to the fieldlike magnitude. However for the C_4 coefficient in the Ta 2.4 nm sample, the dampinglike magnitude is almost twice as large as compared to the fieldlike magnitude. This might indicate that C_4 has a different origin as the other coefficient contributions of B_2 and C_1 . As the orthogonal functions, C_2 and B_4 , show non-existing

values, the angular dependence of B_2 and C_4 is confirmed in our samples. The orthogonal function of C_1 , B_1 , shows nonzero values which corresponds to a correction term to the C_1 symmetry.

	Ta 1.2 nm				Ta 2.4 nm			
Parameter	ΔH_X	Err	ΔH_Y	Err	ΔH_X	Err	ΔH_Y	Err
A [Oe]	43.2	± 1.5	36.3	± 1.5	19.32	± 0.05	11.47	± 0.05
B_1 [Oe]	1.1	± 2.1	1.1	± 2.1	-0.26	± 0.07	-0.36	± 0.08
B_2 [Oe]	-11.1	± 2.2	-11.5	± 2.2	-1.79	± 0.08	-1.90	± 0.08
B_3 [Oe]	4.3	± 2.1	4.4	± 2.1	-0.07	± 0.07	0.04	± 0.08
B_4 [Oe]	0.0	± 2.0	0.0	± 2.0	0.00	± 0.07	0.00	± 0.07
C_1 [Oe]	-4.4	± 2.1	-4.2	± 2.1	-0.28	± 0.07	-0.28	± 0.08
C_2 [Oe]	0.0	± 2.0	0.0	± 2.0	0.00	± 0.07	0.00	± 0.07
C_3 [Oe]	-0.6	± 2.1	-0.7	± 2.1	0.05	± 0.07	0.22	± 0.08
C_4 [Oe]	-4.9	± 2.2	-4.5	± 2.2	-0.49	± 0.08	-0.26	± 0.08

Table 1: Parameter of the Fourier analysis for the SOT effective fields for Ta 1.2 nm and Ta 2.4 nm sample.

5.4 ANGULAR DEPENDENCE OF FIELD OFFSET

A field offset in the first harmonic Hall voltage V_ω has also been observed. To determine any significance to our results, the field offset as a function of the azimuthal angle is plotted, as shown in Fig. 48 (a) and 48 (b) for the Ta 1.2 nm and Ta 2.4 nm samples respectively. Two similar anti-symmetric curves in shape are observed. Interestingly, at azimuthal angles of 45° and 225° the field offset in the first harmonic Hall voltage changes sign. This behavior suggests that an intrinsic in-plane anisotropy field is causing the field offset. The magnitude of the maximum field offset change is ~ 380 Oe for the Ta 1.2 nm sample and ~ 90 Oe for the Ta 2.4 nm sample. Measurement-related causes of this field offset can be excluded as the position of the sample and Hall probe within the magnetic field have been varied to confirm the intrinsic origin. Also, to exclude the effect of oxidization on the Ta capping layer, another sample with same layer composition was fabricated with an additional 2 nm ruthenium capping layer on top of the Ta layer. By patterning and measuring this sample with 2 nm of ruthenium capping, similar field offset behavior was confirmed, as shown in section B.5. Similar field offset behavior has been found in exchange biased systems using an AFM layer [133]. They attribute the field offsets in orthogonal in-plane directions from first harmonic Hall voltage signals to different EB fields which is similar to the measured field offsets as measured in Fig. 48.

Figure 48: (a) First harmonic Hall voltage as a function of the applied field directed at $\phi_H = 30^\circ$ (black squares) and at $\phi_H = 60^\circ$ (red dots) for the Ta 1.2 nm sample showing an angular dependence of a field offset. (b) show the angular dependence of the field offset H_{offset} for the Ta 1.2 nm and Ta 2.4 nm sample. The current density was set to $2 \times 10^{10} \text{ A/m}^2$.

5.4.1 Large field sweeps for the Ta 1.2 nm sample

To determine the effect on the first harmonic Hall resistance at large fields, in-plane external field sweeps in a range of ± 4 kOe for the Ta 1.2 nm sample at 45° steps of the azimuthal angle have been performed. The field sweeps can be seen in Fig. 49. Field sweeps in Figs. 49 (a) and 49 (b) in the same row show identical behaviors for low magnetic fields as confirmed by theory. For instance, the field sweep at angle 45° is shown next to the field sweep at angle 225° which corresponds to a 180° rotation and satisfies the $\sin 2\phi$ -symmetry. In a low field regime of ± 500 Oe for $+z$ oriented magnetization, a constant Hall resistance is observed for angles 45° and 225° . This is in line with Fig. 46 (a), where the b_ω coefficient is close to zero, which indicates that $\zeta \approx 0.5$. For $-z$ -axis oriented magnetization, the constant Hall resistance is observed at angles 135° and 315° . At azimuthal angles other than that (90° , 180° , 270° , 360°), symmetric behaviors are expected. Interestingly, the DWM, which is attributed to the magnetization reversal during the field sweep, changes its direction at azimuthal angles of 45° and 225° . The same angles correspond to the sign change of the field offset in the first harmonic Hall resistances (Fig. 48 (a) and 48 (b)). This is striking as an intrinsic transformation of the anisotropy might take place resulting in opposite DW depinning fields and DWMs. We suspect therefore the intrinsic origin the field offset or EB-like effect which is usually related to SOI.

Figure 49: Large field sweeps for $\Delta\phi_H = 45^\circ$ steps for Ta 1.2 nm sample. (a) shows the field sweeps for 45° until 180° . (b) shows the field sweeps for 225° until 360° . The current density was set to 2×10^{10} A/m².

5.4.2 Fitting of the field offset

We noted that the field offset as a function of the azimuthal angle obtains a similar trend which has been found for the β coefficient corresponding to the dampinglike field along the x-direction. This suggests a constant in-plane EB-like field directed along the wire long axis, as shown in Fig. 50.

Figure 50: Schematic of proposed intrinsic exchange bias field causing the magnetization of the Co/Ni multilayers to bend.

The field offsets have been plotted again and fitted using the β coefficient to the data points, as shown in Fig. 51 (a) and (b) for the Ta 1.2 nm and Ta 2.4 nm sample respectively. The fitting parameter can be seen in Table 2. The β -fitting function is well fitted to the data points suggesting a constant unidirectional EB field along the x-direction. However, as the β function is the coefficient for the dampinglike field which is only present in the second harmonic Hall voltage, we try to analytically derive the fitting function. As suggested by the β -function, a constant field in x-direction in the energy balance equation is introduced. This constant field is labeled here as EB field as the trend follows the traditional definition of an EB field. The EB field is proposed as intrinsic in origin emerging from a slight tilting of the magnetization towards the x-direction from the dominating PMA in the magnetic structure, as shown in Fig. 50. Hence, a small EB field is expected from the canting of neighboring magnetic moments in the structure. The energy balance equation is then given by

$$E = -K_{Eff} \cos^2 \theta - K_I \sin^2 \varphi \sin^2 \theta - \vec{M} \bullet \vec{H} - \vec{M} \bullet \vec{H}_{EB}, \quad (128)$$

where K_{Eff} is the effective out-of-plane anisotropy constant, K_I the effective in-plane anisotropy constant, $\vec{M}$ is the magnetization, θ is the polar angle of the magnetization, φ is the azimuthal angle of the magnetization, $\vec{H}$ is the external field and $\vec{H}_{EB}$ is the introduced EB field. The stable polar and azimuthal angles of the magnetization then can be calculated by executing $\partial E / \partial \theta = 0$ and $\partial E / \partial \varphi = 0$. Supposing a negligible in-plane anisotropy the magnetization angles are obtained by

$$\sin \theta = \frac{H_{Y-ext} \sin \varphi + (H_{EB} + H_{X-ext}) \cos \varphi}{H_K}, \quad (129)$$

$$\tan \varphi = \frac{H_{Y-ext}}{H_{EB} + H_{X-ext}}. \quad (130)$$

The first harmonic Hall voltage is given by Eq. (84) as

$$V_\omega = \frac{1}{2} I_{ac} [\Delta R_A \cos \theta + \Delta R_{P\&S} \sin^2 \theta \sin 2\varphi]. \quad (131)$$

Using the approximation $\cos \theta \approx 1 - \frac{1}{2} \sin^2 \theta$ and Eq. (129), the first harmonic Hall voltage is given by

$$\begin{aligned} V_\omega = \frac{1}{2} I_{ac} & \left(\Delta R_A \left(1 - \frac{1}{2} \frac{[H_{Y-ext} \sin \varphi + (H_{EB} + H_{X-ext}) \cos \varphi]^2}{H_K^2} \right) \right. \\ & \left. + \Delta R_{P\&S} \frac{[H_{Y-ext} \sin \varphi + (H_{EB} + H_{X-ext}) \cos \varphi]^2}{H_K^2} \sin 2\varphi \right). \end{aligned} \quad (132)$$

In terms of the factor ζ , Eq. (132) reformulates to

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} I_{ac} \Delta R_A [1 - 2\zeta \sin 2\varphi] \frac{[H_{Y-ext} \sin \varphi + (H_{EB} + H_{X-ext}) \cos \varphi]^2}{H_K^2}. \quad (133)$$

Using $\sin \varphi = \frac{\tan \varphi}{\sqrt{1+\tan^2 \varphi}}$, $\cos \varphi = \frac{1}{\sqrt{1+\tan^2 \varphi}}$ and $\sin 2\varphi = 2 \sin \varphi \cos \varphi$, Eq. (133) leads to

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} \left[1 - 4\zeta \frac{\tan \varphi}{1 + \tan^2 \varphi} \right] \frac{(H_{Y-ext} \tan \varphi + H_{EB} + H_{X-ext})^2}{1 + \tan^2 \varphi}. \quad (134)$$

Using Eq. (130), Eq. (134) leads to

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} \left[1 - 4\zeta \frac{(H_{EB} + H_{X-ext}) H_{Y-ext}}{(H_{EB} + H_{X-ext})^2 + H_{Y-ext}^2} \right] \frac{(H_{Y-ext}^2 + (H_{EB} + H_{X-ext})^2)^2}{(H_{EB} + H_{X-ext})^2 + H_{Y-ext}^2}. \quad (135)$$

Reformulating leads to

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} [(H_{EB} + H_{X-ext})^2 + H_{Y-ext}^2 - 4\zeta (H_{EB} + H_{X-ext}) H_{Y-ext}]. \quad (136)$$

Substituting $H_{X-ext} = H \cos \varphi_H$ and $H_{Y-ext} = H \sin \varphi_H$ as the external field is rotating in the plane, Eq. (136) can be reformulated to

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} [H^2 (1 - 2\zeta \sin 2\varphi_H) + H (2H_{EB} \cos \varphi_H - 4\zeta H_{EB} \sin \varphi_H) + H_{EB}^2]. \quad (137)$$

In the last step $\sin 2\varphi_H = 2 \sin \varphi_H \cos \varphi_H$ was utilized. With $f(x) = ax^2 + bx + c$ the vertex (field offset) of the parabola is usually described by $x_{offset} = -b/2a$ which gives for the first harmonic Hall voltage

$$H_{offset} = -\frac{H_{EB} \cos \varphi_H - 2\zeta H_{EB} \sin \varphi_H}{1 - 2\zeta \sin 2\varphi_H}. \quad (138)$$

Figure 51: (a) and (b) show the fits to the data points according to Eq. (93) and (138) as a function of the azimuthal angular for (a) the Ta 1.2 nm and (b) the Ta 2.4 nm sample. (c) and (d) show the respective fits to the data points according to Eq. (141) including an offset angle (φ_E) with respect to the x-axis for (c) the Ta 1.2 nm and (d) the Ta 2.4 nm sample.

The field offset can now be fitted to the data points with the derived formula, as shown in Fig. 51 (a) and (b). The fitting parameters are listed in Table 2. Interestingly, the fits of H_{offset} and $\Delta H_X \beta$ overlap. Consequently, the derived formula for H_{offset} correlates to the β -symmetry leading to $H_{EB} = \frac{1}{2} \Delta H_X$. We suspect the factor 1/2 is the so-called Thomas factor leading to an energy term of $E_{EB} = -\frac{1}{2} \vec{H}_{EB} \cdot \vec{M}$. It should be noted, a marginal increased value of ζ is obtained from the fit as compared to the previous determined factor of ζ . However, fitting the data points with the previously determined ζ factor leads to irrelevant changes to the fit why the difference in ζ is neglected for further discussion. Extending the EB field (H_{EB}) to arbitrary azimuthal angles, the EB field is given by $\vec{H}_{EB} = H_{EB}(\cos \varphi_E, \sin \varphi_E, 0)^T$. Substituting the EB field with azimuthal angle φ_E into the Eq. (128) will change the angles as

$$\sin \theta = \frac{(H_{Y-EB} + H_{Y-ext}) \sin \varphi + (H_{X-EB} + H_{X-ext}) \cos \varphi}{H_K}, \quad (139)$$

$$\tan \varphi = \frac{H_{Y-EB} + H_{Y-ext}}{H_{X-EB} + H_{X-ext}}. \quad (140)$$

Deriving the field offset with the adapted magnetization angles θ and φ the field offset is given by

$$H_{offset} = -\frac{H_{EB} \cos(\varphi_E - \varphi_H) - 2\zeta H_{EB} \sin(\varphi_E + \varphi_H)}{1 - 2\zeta \sin 2\varphi_H}. \quad (141)$$

Parameter	Ta 1.2 nm			Ta 2.4 nm		
	β	H_{X-EB}	H_{EB}, φ_E	β	H_{X-EB}	H_{EB}, φ_E
R_{Adj}	0.949	0.949	0.997	0.963	0.963	0.979
H_{offset} [Oe]	124.4	62.2	58.8	55.3	57.7	23.9
$\Delta(H)$ [Oe]	± 4.6	± 2.3	± 1.5	± 1.6	± 0.8	± 0.7
ζ	0.487	0.487	0.484	0.430	0.430	0.415
$\Delta(\zeta)$	± 0.001	± 0.001	± 0.001	± 0.005	± 0.005	± 0.005
C [Oe]	9.0	9.0	9.0	-11.1	-11.1	-11.1
$\Delta(C)$ [Oe]	± 2.5	± 2.5	± 2.5	± 0.6	± 0.6	± 0.5
φ_E [rad]	—	—	4.86	—	—	5.97
$\Delta(\varphi_E)$ [rad]	—	—	± 0.04	—	—	± 0.05

Table 2: Parameter of the fits according to Eqs. (93, 138, 141) for the field offset in the first harmonic Hall voltage for Ta 1.2 nm and Ta 2.4 nm sample.

The fitting of the H_{offset} according to Eq. (141) is shown in Figs. 51 (c) and (d). The constant offset C corresponds to an offset field which is caused by a mismatch of the exact field value at the device and the field value at the placed Hall probe next to the device. The fit of H_{EB}, φ_E to the data points is found to have a significant improvement for the Ta 1.2 nm sample as compared to the fit for H_{EB} directed at the fixed orientation along the x-axis. This is also manifested from the improved adjunct R function, as well as from the reduced error $\Delta(H)$ of the field offset and the large offset angle from the x-axis which reads $4.86 \text{ rad} \equiv 278^\circ$. For the Ta 2.4 nm sample the improvement is minimal which should be related to the smaller offset angle, φ_E , with respect to the x-axis which reads $5.97 \text{ rad} \equiv 342^\circ$. As a consequence, the direction of the in-plane **EB** field, φ_E , is not necessarily directed along the x-axis. The arbitrary direction of the **EB** field should be preferably a result of the thin film deposition and grain size than related to the shape anisotropy. It should be noted, that **EB** fields usually occur in **FM**/**AFM** bilayer structures [101, 116]. Oxidation of films such as CoO and NiO also exhibit antiferromagnetic behavior which we exclude as the cause for our systems, as the **FM** layers were deposited at low base pressures and capped by Ta. We suggest the Ta capping layer might control the grain size of the polycrystalline **FM** layer which has an effect on the **EB** [145, 126, 55, 180]. The dilution of diffusive Ta into **FM** Co layer can also introduce some effect, but with increasing Ta thickness a decay in **EB**-like effect as well as in out-of-plane anisotropy is observed.

Cain and Kryder observed **EB**-like effect in NiFe/TbCo bilayers which is a **FM**/**FM** system different from the general systems [22]. They explained their result by a tilt of spins at the **FM**/**FM** interface. It should be noted that TbCo is amorphous whereas NiFe is considered polycrystalline in the study which is similar to our study where the Co/Ni

multilayer structure can be considered polycrystalline and the Ta capping layer is usually amorphous. However, the EB-like effect decreases with increasing Ta thickness which suggests the amorphous/polycrystalline interface is not the crucial factor. Bollero et al. explained his observation of EB-like phenomenon in a NiFe/(Pt/Co) multilayer structure by means of a closure domain (vortex core) model formed at the FM/FM interface [15, 16]. This could also happen at the Co/Ni interfaces where the Co layers are responsible for the PMA whereas the Ni layers can be responsible for the canting of spins locking the spins in a specific in-plane direction [113]. The control of this effect *via* the Ta capping thickness might be through the control of grain size for the FM multilayers.

Obtaining an intrinsic EB-like effect without the need of an AFM is actually striking and might have potential for low power SOT magnetization switching as for PMA structures usually an in-plane bias field is required which can be replaced by an intrinsic exchange-bias field, as shown by several studies [52, 85, 79, 83, 133, 17]. Here, a path without the need of an AFM layer is provided which simplifies the architecture for device integration by tailoring the thicknesses of the FM multilayers (soft/hard anisotropy FM layers) and top and bottom layers to control the EB field required for external field-free SOT magnetization switching. The proof of concept for such a scenario has been shown by Li et al. in an almost identical Pt/(Co/Ni)₂/Co/Ta structure [87].

5.5 INFLUENCE OF EXCHANGE BIAS FIELD ON SOT FIELDS

In this section, an analytical investigation to show the influence of the exchange bias field on the SOT field determination is presented based on the symmetries of AHE and PHE&SMR in the Hall voltage signal. Therefrom, the validity of the determined SOT fields in presence of the EB-like field offset is investigated. The derivative of the second harmonic Hall voltage, $b_{2\omega}$, has been determined in section B.4 which is given by

$$b_{2\omega} = \frac{\partial V_{2\omega}}{\partial H} = \frac{I_{ac}\Delta R_A}{2H_K^2} \left(\Delta H_Y \left(\frac{1}{2} \sin \varphi_H - \xi \cos \varphi_H \right) + \Delta H_X \left(\frac{1}{2} \cos \varphi_H - \xi \sin \varphi_H \right) \right). \quad (142)$$

For the calculation of the first harmonic Hall voltage, we start from Eq. (136) and making the following exchanges to introduce the offset angle φ_E for the EB field as given by

$$H_{EB} \xrightarrow{\varphi_E} H_{X-EB} = H_{EB} \cos \varphi_E$$

$$H_{Y-ext} \xrightarrow{\varphi_E} H_{Y-ext} + H_{Y-EB} = H \sin \varphi_H + H_{EB} \sin \varphi_E.$$

The first harmonic Hall voltage is then examined by

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} \left[(H_{X-EB} + H_{X-ext})^2 + (H_{Y-EB} + H_{Y-ext})^2 - 4\zeta(H_{X-EB} + H_{X-ext})(H_{Y-EB} + H_{Y-ext}) \right]. \quad (143)$$

Inserting the respective field components H_{X-EB} , H_{Y-EB} , H_{X-ext} and H_{Y-ext} leads to

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} \left[H^2 + H_{EB}^2 + 2HH_{EB} \cos \varphi_E \cos \varphi_H + 2HH_{EB} \sin \varphi_E \sin \varphi_H - 4\zeta \left(H_{EB}^2 \cos \varphi_E \sin \varphi_E + HH_{EB} (\cos \varphi_E \sin \varphi_H + \sin \varphi_E \cos \varphi_H) + H^2 \cos \varphi_H \sin \varphi_H \right) \right]. \quad (144)$$

Restructuring in terms of H and using trigonometric identities give

$$V_\omega = \frac{1}{2} I_{ac} \Delta R_A - \frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} \left[H^2 (1 - 2\zeta \sin 2\varphi_H) + 2HH_{EB} [\cos(\varphi_E - \varphi_H) - 2\zeta \sin(\varphi_E + \varphi_H)] + H_{EB}^2 (1 - 2\zeta \sin 2\varphi_E) \right]. \quad (145)$$

Assuming H is independent of H_{EB} which should be the case as H_{EB} is found to be constant, the second derivative in H is derived previously in section 4.2.3 as

$$b_\omega = -\frac{1}{2} \frac{I_{ac} \Delta R_A}{H_K^2} (1 - 2\zeta \sin 2\varphi_H). \quad (146)$$

The ratio B_{φ_H} can be derived which, then, obtains the same form as in section 4.2.3 considering the equivalence as computed in section B.3 which give

$$B_{\varphi_H} = -\frac{\Delta H_Y (\frac{1}{2} \sin \varphi_H - \zeta \cos \varphi_H) + \Delta H_X (\frac{1}{2} \cos \varphi_H - \zeta \sin \varphi_H)}{1 - 2\zeta \sin 2\varphi_H}. \quad (147)$$

As a result, the same form for the SOT effective fields as derived in section 4.2.3 [Eqs. (101, 102)] are obtained with

$$\alpha = -\frac{\frac{1}{2} \sin \varphi_H - \zeta \cos \varphi_H}{1 - 2\zeta \sin 2\varphi_H},$$

$$\beta = -\frac{\frac{1}{2} \cos \varphi_H - \zeta \sin \varphi_H}{1 - 2\zeta \sin 2\varphi_H}.$$

For magnetization aligned along the $-z$ -axis, the form of α and β functions as derived in section B.3 can be used. Hence, the derived equation for the determination of SOT effective fields as a function of azimuthal angles in presence of an in-plane EB field is still valid and no correction to the previous derived equations in section 4.2.3 has to be made. Any influence of the EB field on the SOT fields must be investigated using in-depth analysis.

5.6 LONGITUDINAL VOLTAGE MEASUREMENT TO DISTINGUISH PHE AND SMR

Figure 52: Second derivative of the first harmonic longitudinal voltage, V_X , with respect to the applied field as a function of the azimuthal angle of the applied field for the Ta 2.4 nm sample. The fit to the data points was performed using Eq. (148).

In this section, the first harmonic longitudinal voltage of the wire is measured as a function of the in-plane applied field for various azimuthal angles. The respective second derivatives of the voltage V_X with respect to the applied field ($b_\omega = \frac{\partial^2 V_X}{\partial H^2}$) are shown in Fig. 52. As the voltage of the wire is simultaneously measured with the AC, the obtained SNR is decreased as compared to Hall measurements. However, a clear sinusoidal trend is observed which can be fitted according to PHE and SMR theory from Eqs. (57, 60) as

$$f(x) = A * \sin^2(x) + B * \cos^2(x) + C. \quad (148)$$

The fit to the data points can be seen in Fig. 52. The clear $-\sin^2(\phi_H)$ -signal indicates a predominantly contribution of SMR as compared to PHE which is in line with the assumption of a weak PHE in PMA structures and confirms recent results indicating the SMR as source for the obtained symmetry in harmonic Hall measurement determination [77]. The fitting parameters A and B have been obtained by

$A = -1.46 \times 10^{-10} \text{ V/Oe}^2$ and $B = 2.8 \times 10^{-11} \text{ V/Oe}^2$. These values are comparable to the value obtained from Fig. 46 (b) from the Hall voltage measurement as $\Delta b_\omega \approx -1.26 \times 10^{-10} \text{ V/Oe}^2$ which confirms the major contribution arising from SMR rather than PHE. This has a huge effect on the SOT determination using harmonic Hall technique as many people neglect this symmetry as PHE is usually small in PMA structures or sometimes this symmetry effect is even wrongly stated in the harmonic signal as caused by PHE.

5.7 DISCUSSION OF THE INFLUENCE OF SMR TO SOT FIELDS

As the PHE-symmetry signal in the SOT determination has been confirmed to arise from SMR effect, the influence caused from the SMR effect to the angular dependence of SOT effective fields is discussed here. In the SMR theory, the relative orientation of the magnetization vector with respect to the spin accumulation orientation due to SHE in the NM layer is usually described by the GMR effect [5]. The spin accumulation, $\vec{p}$, at the FM/NM interface for a current density in x-axis direction are oriented along y-axis direction with the surface normal oriented in z-axis direction, as shown in Fig. 53.

Figure 53: Schematic drawing explaining the SMR effect. (a) shows a predominant absorption of the spin current into the ferromagnetic layer for $\hat{p} \perp \hat{m}$ whereas (b) shows a predominant reflection of the spin current back to the nonmagnetic layer for $\hat{p} \parallel \hat{m}$.

When the spin accumulation at the interface and the magnetization are in parallel orientation, $\hat{p} \parallel \hat{m}$, the spin current from the NM layer is reflected back. When the spin accumulation at the interface and the magnetization are in perpendicular orientation, $\hat{p} \perp \hat{m}$, the spin current from the NM layer is absorbed into the FM layer providing STT, as shown in Fig. 53 [112, 159]. This symmetry of the spin current diffusing into the FM layer is well replicated by $m_y^2 - 1$. Using this

simplistic model for the magnetization direction dependence, the **SOT** effective fields in the **FM** layer are described using Eqs. (52, 53) as

$$\vec{H}_{FL} = \frac{a}{\gamma} \hat{p} = \frac{a}{\gamma} \begin{pmatrix} 0 \\ m_y^2 - 1 \\ 0 \end{pmatrix}, \quad (149)$$

and

$$\vec{H}_{DL} = \frac{b}{\gamma} \hat{p} \times \vec{M} = M_S \frac{b}{\gamma} \begin{pmatrix} m_z(m_y^2 - 1) \\ 0 \\ -m_x(m_y^2 - 1) \end{pmatrix}. \quad (150)$$

With $m_z \approx 1$ the dampinglike and fieldlike **SOT** effective fields exhibit the same symmetry with respect to the magnetization orientation. However, the observed **SOT** angular dependence due to the magnetization vector rotation is different from the computed angular dependence using the simplified **SMR** model. These findings suggest a more complicated behavior of the interface effects where spin pumping from the **FM** layer into the **NM** layers or the imaginary spin-mixing conductance might play an important role. With $\xi = 0.146$ in the **IrMn** sample where the $-\sin 2\varphi$ -symmetry is absent, with $\xi = 0.204$ in the **BTO** sample obtaining a weak $-\sin 2\varphi$ -symmetry, with $\xi \approx 0.40$ in the Ta 2.4 nm sample obtaining a strong $-\sin 2\varphi$ -symmetry and with $\xi \approx 0.48$ in the Ta 1.2 nm sample obtaining a colossal $-\sin 2\varphi$ -symmetry, a correlation of **SMR** effect and the **SOT** effective field angular dependence is suggested.

5.8 SUMMARY

In summary, harmonic Hall measurements for two samples with various Ta capping thicknesses have been performed. The thickness of the Ta capping has been shown to affect all magnetic parameters of the **FM** heterostructure such as coercivity, **PMA**, **AHE**, **SMR**, **EB** and **SOT** effective fields. Large ξ factors of the **PHE&SMR** to **AHE** resistance ratio of up to ~ 0.48 have been found. The symmetry of **SOT** effective fields on the magnetization azimuthal angle has been characterized to be predominantly showing a $-\sin 2\varphi$ -symmetry. A second $-\cos 4\varphi$ -symmetry is found which might originate from a different effect. Field offsets of the first harmonic Hall voltage have been analyzed and shown to change sign at the same azimuthal angles at 45° and 225° . Large field sweeps indicate that at angles 45° and 225° the **DWM** reverses direction in the wire which also indicates an intrinsic transformation of the anisotropy. The field offset as a function of the azimuthal angle has been derived and show a unidirectional in-plane **EB**-like field as can be obtained from fits to our data points. This is striking as **EB** fields are usually found in **FM/AFM** bilayer structures. **Bollero et al.** argued

in a perpendicular anisotropy/ in-plane anisotropy heterostructure the EB-like phenomenon is caused by a closure domain (vortex core) model formed at the FM/FM interface [15, 16]. Accordingly, the EB-like field measured in our structure might arise from the Co/Ni interfaces which, in turn, can be controlled *via* the Ta capping thickness through tailoring of the grain size.

The in-plane EB-like field has been incorporated into the SOT determination, which does not affect the previously derived SOT equations in chapter 4. By measuring the longitudinal voltage of the wire as a function of applied field at various azimuthal angles, the PHE and SMR signals from the Hall measurements can be separated and the major contribution can be attributed to the SMR. The current SMR model due to spin-dependent scattering at the HM/FM interface does not replicate the quantified SOT angular dependence suggesting a more complicated interface behavior of the HM/FM interface. Our findings lay the corner stone for SOT effective field angular dependence on the magnetization azimuthal angle. Also, the foundation to analyze SOT effective fields in the presence of an exchange bias field was laid out. This is usually the case by the integration of an AFM material into PMA structures to switch the magnetization without the necessity of an external field.

CONCLUSION & OUTLOOK

6.1 CONCLUSION

In conclusion, magnetization switching in a Pt/(Co/Ni)₄/Co/IrMn stack structure with PMA and exchange bias has been investigated. Using differential Kerr imaging microscopy technique, magnetization switching *via* DWM has been shown. Field-driven DW depinning and motion was performed as an alternative characterization tool to quantifying the SOT effective fields which was compared with harmonic Hall voltage modulation technique to characterize SOT effective fields. The PHE correction in the harmonic Hall voltage technique was identified to be of profound importance. Additionally, the bias current in the wire leads to a decrease in both, the out-of-plane coercivity and effective out-of-plane anisotropy field which is attributed to SOT effective fields within the system.

Taking the PHE and the newly discovered SMR into consideration, a framework was mathematically derived to quantify SOT effective fields as a function of the magnetization azimuthal variation by means of harmonic Hall voltage technique for structures with PMA. The method is based on the magnetic energy balance equation in the low external field limit ($\sim H_{max} < \frac{1}{3}H_K$) and is able to cross-check the derived SOT fields as a function of the azimuthal angle using voltage parameters at φ_H and $90^\circ - \varphi_H$ on one side and φ_H and $270^\circ - \varphi_H$ to cross-check. Experimental study was carried out on Pt/Co/Pt/Co/Ta/BTO test sample to verify the derived model. The dampinglike term for the BTO sample shows a noticeable angular dependence in both calculated $H_{DL} - \varphi_H$ plots which have been calculated using voltage parameters at different azimuthal angles whereas no noticeable angular dependence of the fieldlike term is observed (parameters for φ_H and $90^\circ - \varphi_H$ calculation for one plot and parameters for φ_H and $270^\circ - \varphi_H$ for the second plot). The angular dependence of the dampinglike term obtains minima at 45° and 225° . The weakly SOT effective fields dependence due to the magnetization azimuthal angle variation is in agreement with previous assumptions [53].

Measuring the SOT effective fields as a function of the azimuthal angle for two samples of Pt/(Co/Ni)₂/Co/Ta layer structure with large ξ factors of $\xi = \frac{R_{PHE+SMR}}{R_{AHE}} \approx 0.48$ and $\xi \approx 0.40$, large SOT field dependencies on the magnetization azimuthal angle have been found. The symmetry of SOT effective fields on the magnetization azimuthal angle has been characterized to be predominantly showing a $-\sin 2\varphi$ -

symmetry with a weak $-\cos 4\phi$ -symmetry. Computed out-of-plane anisotropy fields as a function of the azimuthal angle exhibit extrema at azimuthal angles 45° and 225° with respect to the current direction. In general, the out-of-plane anisotropy field should be constant with azimuthal angle, as shown for the [IrMn](#) sample in section [A](#).

Field offsets in the first harmonic Hall voltage signal have been analyzed and attributed to an in-plane [EB](#) field which is unusual in a [FM/HM](#) heterostructure but was already found in [FM/FM](#) bilayers with weak/strong out-of-plane anisotropy structures [[15](#), [16](#), [113](#)].

The obtained field offset changes sign for both samples at azimuthal angles of 45° and 225° . Large field sweeps at various azimuthal angles show the reverse of direction of intrinsic [DWM](#) at same angles of 45° and 225° indicating an intrinsic transformation of the anisotropy. The field offsets as a function of the azimuthal angle have been derived and show a unidirectional in-plane [EB](#)-like field as can be obtained from fits to our data points with no direct implications on the anisotropy determination which suggests intrinsic connections *via* [SOI](#). Incorporating an [EB](#)-like field into the model for [SOT](#) field determination as a function of the azimuthal angle leaves the derived model in chapter [4](#) unchanged.

[SMR](#) and [PHE](#) signals can be separated by measuring the longitudinal voltage of the wire as a function of applied field at various azimuthal angles. We identify the major contribution arises due to the [SMR](#) with little contribution from the [PHE](#). I propose that the [SMR](#) signal is responsible for the measured $-\sin 2\phi$ angular dependence symmetry of [SOT](#) effective fields showing identical symmetry to the [SMR](#) voltage.

6.2 OUTLOOK

Following this work, a framework to measure [SOT](#) effective fields as a function of the magnetization azimuthal angle has been derived which can be used to measure [SOT](#) fields in various multilayer systems with [PMA](#). The angular dependence of [SOT](#) fields, then, can be compared with various magnetic properties of the sample such as coercive, [EB](#) and out-of-plane anisotropy fields. We showed, that a large contribution of the Hall resistance arises due to [SMR](#). As the [SMR](#) has not been studied extensively in [FM/HM](#) multilayer structures so far, we propose the investigation of [SMR](#) using the derived magnetization angular dependence measurement scheme of [SOT](#) effective fields. As the [SMR](#) is proposed to arise from spin-dependent backscattering and absorption of electrons at the [FM/HM](#) interface [[112](#)], the derived measurement scheme is an excellent tool to probe angular dependent [SOT](#) effective fields as a function of [SMR](#). As shown, the [SMR](#) contribution can be varied by the control of the thickness of the capping layer. The behavior of the [SOT](#) field angular dependence as a function of current density or temperature might be also from profound interest in order

to quantify the underlying physics in terms of temperature dependent effects such as anomalous Nernst effect (ANE) or spin Seebeck effect.

Figure 54: Schematic of the proposed ferroelectric / ferromagnetic bilayer structure. In the vicinity of the screening length from the ferroelectric / ferromagnetic interface, the conduction electron experiences a magnetic field, $\vec{B}$.

Further, we propose another study that can focus on the investigation of the Rashba effect in a FM/ferroelectric insulator (FE) bilayer system, as shown in Fig. 54. Such a system has been recently shown to deterministically switch the magnetization [21]. While this study was performed using a crystalline FE substrate with a Pt separation layer to the FM layer, epitaxial FE thin film layers such as BTO can be deposited by means of pulsed laser deposition (PLD) [88, 115, 19]. By tailoring the crystalline lattice structure, the electric field and therefore the current-induced magnetic field direction can be varied. This is very interesting to investigate the underlying physics as the separation of Rashba effect and SHE are usually complicated. The underlying physics of the Rashba effect is nontrivial and yet requires further understanding. As Rashba effect is usually attributed to induce fieldlike field only, the study with negligible SHE can focus on the investigation of both, fieldlike and dampinglike fields. Angular dependent measurements can also provide more insight to the origin of Rashba effect which can be tested by various theoretical approaches such as free electron theory, tight-binding theory, quantum Boltzmann approach, quantum tunneling theory or more. The angular dependent SOT fields can also be measured as a function of the crystallographic lattice orientation of the FE and/or the adjacent FM layers. The crystallographic lattice orientation of the FE layer usually determines the orientation of the induced electric field and is therefore of profound interest. XRD or TEM experiments are required to identify the symmetry of the lattice structure. Various deposition conditions and/or varying sublayer configuration prior to deposition are interesting studies to varying the crystallographic axis of the FE layer. By annealing effect, which can

improve or deteriorate the crystallinity and thus the magnitude of the electric field, various parameters can be varied and investigated.

As we have shown in this thesis, an in-plane **EB**-like field in a $\text{Pt}/(\text{Co}/\text{Ni})_2/\text{Co}/\text{Ta}$ structure is observed. This is one of the rare observations of **EB** field without the usage of an adjacent **AFM** layer and therefore very interesting for further investigation. We showed, that the **EB** field magnitude is varied by means of the Ta capping layer thickness. Further investigation is required in terms of thicknesses of Co, Ni and Pt underlayer on the **EB** magnitude and grain size, which can be studied by transmission electron microscopy and atomic force microscopy. Also, to image the magnetic domain configuration would be interesting by using Kerr imaging technique.

The in-plane **EB** field provided from an adjacent **AFM** layer has also been shown to assist the **SOT**-induced magnetization reversal [52, 85]. Using the multilayer structure investigated, $\text{Pt}/(\text{Co}/\text{Ni})_2/\text{Co}/\text{Ta}$, the intrinsic **EB** field also lead to magnetization reversal which can be further investigated.

SUPPLEMENTARY INFORMATION FOR CHAPTER 4

The plots for the IrMn sample to obtain SOT effective fields as a function of the magnetization azimuthal angle are provided in this chapter. Additional anisotropy field plots are shown in section A.4 for the IrMn sample to evaluate the accuracy of the ζ ratio and support the argument that the out-of-plane anisotropy field decrease is due to SOT effective fields.

A.1 DETERMINATION OF THE ζ RATIO FOR IRMN SAMPLE

In analogy to the ζ resistance ratio determination in section 4.4, first harmonic Hall voltages are measured for azimuthal angles of $\pm 45^\circ$, as shown in Fig. 55 (a). The AHE resistance was obtained by 0.641Ω . From Eqs. (117-119) the parameters $\Delta\tilde{R}_H^-$ and $[1 - (\Delta\tilde{R}_H^+)^2]$ are computed and plotted against each other, as shown in Fig 55 (b).

Figure 55: (a) Hall resistance as a function of applied field swept along azimuthal angles of $\pm 45^\circ$ for the IrMn sample. The polar angle θ_H is set to $\pi/2$. The subtracted normalized resistance $\Delta\tilde{R}_H^-$ as a function of $[1 - (\Delta\tilde{R}_H^+)^2]$ and linear fit to the data points.

The slope of the linear fit corresponds to the ζ factor as obtained by 0.146 ± 0.001 . With the knowledge of this ζ factor, SOT effective fields are computed as explained in section A.3. The ζ value is further used in section A.2.

A.2 ANGULAR DEPENDENCE OF HALL VOLTAGES FOR THE IRMN SAMPLE

The obtained derivatives of the respective first and second harmonic Hall voltages are shown in Fig. 56 (a) and (b). Here, a predominantly $-\cos \varphi_H$ -symmetry is found for the $b_{2\omega}$ values with respect to the azimuthal angle φ_H whereas a $-\sin 2\varphi_H$ -symmetry is obtained for the b_ω values. These symmetries are opposite as compared to the values for the BTO sample in section 4.6 in Fig. 44 which is a result of the oppositely magnetized sample.

Figure 56: Angular dependence of (a) $b_{2\omega}$, (b) b_ω , (c) B_{φ_H} with fit according to Eq. (91) and (d) the residual of the B_{φ_H} -fit for IrMn sample. The AC bias current density in the wire was set to 1×10^{11} A/m² with the magnetization initially magnetized along the $-z$ -axis orientation.

The ratio of the second harmonic to first harmonic Hall voltage derivatives, B_{φ_H} , is plotted in Fig. 56 (c). The angular variation of B_{φ_H} is in good agreement with Eq. (90), as seen by the fitting curve in Fig. 56 (c). This implies that our theoretical derivation is in good approximation with the experimental measurements. The residual of the fit is shown in Fig. 56 (d). Similarly to the BTO sample, the data points are not randomly scattered around the fitting function which is shown in Fig. 56 (d). The data points are clearly scattered at a sinusoidal function which implies a weak angular dependence of at least one SOT effective field.

A.3 ANGULAR DEPENDENCE OF SOT EFFECTIVE FIELDS FOR IRMN SAMPLE

To compute SOT effective fields as a function of the azimuthal angle, φ_H , for the IrMn sample, the $\zeta = \frac{\Delta R_{P\&S}}{\Delta R_A}$ ratio as well as the derivatives b_ω and $b_{2\omega}$ have to be measured. The respective plots for the determination of the variables can be seen in section A.1 and A.2. The ratio ζ has been found to 0.146 ± 0.001 for the IrMn sample.

The SOT effective fields can be directly computed from the respective B_φ values (see Fig. 56 (c) in section A.2 for details) as described in section 4.2.3 by Eqs. (101), (102), (107) and (108). The computed SOT effective fields are shown in Fig. 47. For simplicity, the SOT effective fields are averaged as $\Delta H_{X,Y} = [\Delta H_{X,Y}(\varphi_H, 90^\circ - \varphi_H) + \Delta H_{X,Y}(\varphi_H, 270^\circ - \varphi_H)]/2$.

Figure 57: Computed SOT effective fields for the IrMn sample as a function of azimuthal angle φ_H of the applied field with respect to current direction. The current density was 1×10^{11} A/m² for all measurements. (a) Averaged dampinglike field and (b) averaged fieldlike field. The red line corresponds to the average SOT field with respect to the φ_H angle for visibility of the angular dependence. The dashed lines (in orange) correspond to the asymptotes where no fields are computed.

The averaged dampinglike field, $\Delta H_X = H_{DL}$, is computed to 12.1 Oe while the averaged fieldlike field, $\Delta H_Y = H_{FL}$, is computed to 2.8 Oe per 1×10^{11} A/m². Both SOT effective fields exhibit small variations from their respective average value which is plotted as red line in the Figs. 57 (a) and (b) for visibility. We noted in both figures, Figs. 57 (a) and (b), local minima at azimuthal angles of 45° , 135° , 225° and 315° with symmetry-axes where $\alpha^2 = \beta^2$. We further suspect a $-\sin 2\varphi_H$ -symmetry, similar to the dampinglike field for the BTO sample, but for a conclusive evaluation of the angular dependence, a sample with larger angular dependence is required with increased SNR. We expect that this trend can be more pronounced in samples with larger SOT effective fields supported by calculations on a tight-binding model

where angular dependence of SOT is expected for samples with similar magnitude of SOC exchange coupling [86].

A.4 OUT-OF-PLANE ANISOTROPY FIELDS FOR IRMN SAMPLE

Here, the influence of a wrongly stated ζ factor on the determination of the out-of-plane anisotropy field is tested, where the out-of-plane anisotropy is supposed to be constant with respect to the azimuthal angle, φ . In Fig. 58 (a), the computation of various anisotropy fields, H_K , is plotted for ζ values of 0, 0.146 and 0.3. The anisotropy field, H_K , was computed by Eq. (151). A sinusoidal trend is observed for both representative ζ values of 0 and 0.3. However, H_K should not show any angular field dependence as it is an intrinsic material property. For the measured value of $\zeta = 0.146$, irrespective of the angle of applied field, a constant H_K is obtained, which is expected. This confirms that our method of calculating the ζ term is accurate. In Fig. 58 (b), the field, H_K , is plotted as a function of current density in the wire for azimuthal angles of 0° and 90° as no influence of P&S and therefore ζ is expected. A nearly 400 Oe continuously decrease in both H_K -plots is observed as the current density in the wire is increased from 1 to 10×10^{10} A/m². This confirms the observation made in section 3.5.

Figure 58: (a) Computed out-of-plane anisotropy effective fields for the IrMn sample as a function of azimuthal angle φ_H of the applied field for various ζ factors. A constant bias current density of 1×10^{11} A/m² was applied to in the wire. The sample was initially magnetized along the $-z$ -axis orientation. (b) Computed out-of-plane anisotropy effective fields for the IrMn sample as a function of current density at azimuthal angles of 0° and 90° .

SUPPLEMENTARY INFORMATION FOR CHAPTER 5

B.1 CURRENT-INDUCED TEMPERATURE EFFECTS ON THE SOT FIELD DETERMINATION

To quantify current-induced temperature effects on the SOT effective field determination, SOT effective fields as a function of current density and the ANE resistance are obtained. The linearity of SOT fields with respect to current density in the wire is utilized as a measure of thermal effects, as extensively discussed by Kim et al. [76].

Figure 59: (a) SOT effective fields as a function of current density for the Ta 2.4 nm sample. (b) R_ω - H loop as a function of the out-of-plane field for the Ta 2.4 nm sample. The inset shows the second harmonic Hall resistance $R_{2\omega}$ as a function of the out-of-plane field. The current density was set to 2×10^{10} A/m².

The SOT effective fields were characterized in the Ta 2.4 nm sample as a function of current density in the wire using Eqs. (125) and (126). The ζ ratio was obtained from first harmonic Hall voltage sweeps using Eq. (121) to ~ 0.4 for the Ta 2.4 nm sample. The computed SOT effective fields with magnetization pointing along the $+z$ direction are shown as a function of current density with respective linear fits in Fig. 59 (a). Both current-induced SOT effective fields scale linear with current density, J , as expected for low current density. This is in agreement with other observations, where nonlinear contributions of the SOT fields with respect to current density have been obtained in previous studies at values larger than 1×10^{11} A/m² [130, 53]. The SOT effective field efficiencies are calculated to $\chi = H_{SOT} / J = 9.9$ Oe / (10^{10} A/m²) for dampinglike term and $\chi = 6.4$ Oe / (10^{10} A/m²) for fieldlike term. Also, first and second harmonic Hall resistances as a function of the out-of-plane field, H_z , were measured, as shown in Fig. 59 (b). First harmonic Hall resistance reveals an AHE resistance of

$\sim 0.5 \Omega$. The **OHE** can be considered negligible in microstructures. The coercivity is given by ~ 60 Oe. In general, the **ANE** resistance can be taken as the difference in second harmonic Hall resistance for opposite magnetizations, as shown in the inset of Fig. 59 (b). The **ANE** resistance was approximated to ~ 0.02 m Ω . As such, temperature effects are neglected here.

B.2 ANGULAR DEPENDENCE OF ANISOTROPY FIELD

To validate the correlation of the anisotropy field on the **SOT** effective fields, the anisotropy field was computed as a function of the magnetization azimuthal angle from the first harmonic Hall voltage as given by [45]

$$H_K = \sqrt{-\frac{\Delta R_A}{2b_\omega}(1 - 2\xi \sin 2\varphi_H)I_{ac}}. \quad (151)$$

The anisotropy field as a function of the azimuthal angle can be seen in Fig. 60 (a) for Ta 1.2 nm sample and in Fig. 60 (b) for Ta 2.4 nm sample. Surprisingly, two spikes in both plots are observed at angles 45° and 225° . The magnitudes of the spikes are with ~ 550 Oe for the Ta 1.2 nm sample significantly larger as compared to the Ta 2.4 nm sample with ~ 150 Oe. The increase in base anisotropy field of ~ 6.45 kOe for the Ta 1.2 nm sample might play a role here as compared to the base anisotropy field of ~ 4.18 kOe for the Ta 2.4 nm sample. Comparing the anisotropy field with the obtained **SOT** effective fields in section 5.3, maxima for the anisotropy fields at 45° and 225° are found to be shifted by 90° as compared to the **SOT** fields which obtain maxima at 135° and 315° . Similar results have been found in our previous study [44]. We noted, that the magnitude of B_{φ_H} in Fig. 46 (e) for the Ta 1.2 nm sample exhibits also two spikes at angles 45° and 225° . This possible relationship might help in understanding correlations of these effects as the spikes in B_{φ_H} are determined by a large ξ ratio and therefore larger **PHE** or **SMR** in the structure. The spikes might also arise from inaccurate determination of the ratio **AHE** to **PHE** resistances, which have been tested to influence the angular dependence significantly. As such, the obtained angular dependence of the anisotropy field shall be considered with due care.

Figure 60: Angular dependence of the anisotropy field for (a) the Ta 1.2 nm and (b) Ta 2.4 nm sample. The current density was set to 2×10^{10} A/m².

B.3 EQUIVALENCE OF α AND β COEFFICIENTS WITH FIELD OFFSET EQUATION

In this section, the equivalence of both functions, $\Delta H_X \beta$ and H_{Offset} , is validated. As such, one form can be exchanged with the other form, in particular the equation for the field offset can be utilized in order to compute the [SOT](#) effective fields as a function of the azimuthal angle. We start from the β equation [Eq. (93)] which read

$$\beta = -\frac{1}{2} \cos \varphi_H - \frac{\zeta \cos 2\varphi_H}{\pm 1 - 2\zeta \sin 2\varphi_H} \sin \varphi_H. \quad (152)$$

Transforming the formula using a common denominator leads to the built-up fraction as

$$\beta = -\frac{\cos \varphi_H (\pm \frac{1}{2} - \zeta \sin 2\varphi_H) + \zeta \cos 2\varphi_H \sin \varphi_H}{\pm 1 - 2\zeta \sin 2\varphi_H}. \quad (153)$$

Using the identities $\sin 2\varphi_H = 2 \sin \varphi_H \cos \varphi_H$ and $\cos 2\varphi_H = 1 - 2 \sin^2 \varphi_H$, Eq. (153) leads to

$$\beta = -\frac{\cos \varphi_H (\pm \frac{1}{2} - 2\zeta \sin \varphi_H \cos \varphi_H) + \zeta (1 - 2 \sin^2 \varphi_H) \sin \varphi_H}{\pm 1 - 2\zeta \sin 2\varphi_H}, \quad (154)$$

which can be re-written as

$$\beta = -\frac{\pm \frac{1}{2} \cos \varphi_H - 2\zeta \sin \varphi_H (\cos^2 \varphi_H + \sin^2 \varphi_H) + \zeta \sin \varphi_H}{\pm 1 - 2\zeta \sin 2\varphi_H}. \quad (155)$$

Now, the form as obtained in section 5.4.2 is derived in a more simplistic form as

$$\beta = -\frac{\pm \frac{1}{2} \cos \varphi_H - \zeta \sin \varphi_H}{\pm 1 - 2\zeta \sin 2\varphi_H}. \quad (156)$$

This form can be used to replace the function of β derived in section 4.2.3 to compute the angular dependence of SOT effective fields. Similarly, a form for α function can be derived. Here, the point symmetry between α and β is used which gives

$$\begin{aligned}\alpha &= - \left(- \frac{\pm \frac{1}{2} \cos(-\varphi_H) - \zeta \sin(-\varphi_H)}{\pm 1 - 2\zeta \sin(-2\varphi_H)} \right) \\ &= \frac{\mp \frac{1}{2} \cos \varphi_H - \zeta \sin \varphi_H}{\mp 1 - 2\zeta \sin 2\varphi_H}.\end{aligned}\quad (157)$$

B.4 SECOND HARMONIC HALL VOLTAGE COMPUTATION WITH A FIELD OFFSET

Here, a step by step solution for the second harmonic Hall voltage is provided in presence of an in-plane exchange-bias field. The calculation starts from Eq. (85). The angles θ and φ of the magnetization vector are represented in the form of Eqs. (139) and (140). The current-induced angle modulation, $\Delta\theta$ and $\Delta\varphi$, is computed from these angle expressions as

$$\Delta\theta = \frac{\Delta H_Y \sin \varphi + \Delta H_X \cos \varphi}{H_K}, \quad (158)$$

$$\Delta\varphi = \frac{\Delta H_Y (H_{X-EB} + H_{X-ext}) - \Delta H_X (H_{Y-EB} + H_{Y-ext})}{(H_{X-EB} + H_{X-ext})^2 + (H_{Y-EB} + H_{Y-ext})^2}. \quad (159)$$

For $\Delta\theta$ the same form as in Eq. (72) is derived as the approximation $\sin \theta \approx \theta$ was applied. The computation for the second harmonic Hall voltage starts from Eq. (85), which read

$$\begin{aligned}V_{2\omega} &= -\frac{1}{2} I_{ac} \left(\frac{1}{2} [-\Delta R_A \sin \theta + \Delta R_{P\&S} \sin 2\theta \sin 2\varphi] \Delta\theta \right. \\ &\quad \left. + \Delta R_{P\&S} \sin^2 \theta \cos 2\varphi \Delta\varphi \right).\end{aligned}\quad (160)$$

Further, $\sin 2\theta \approx 2 \sin \theta$ is approximated in the next step which utilizes the first order Taylor series at $\theta = 0$. We argue that this approximation is sufficient for our case where both fields, H and H_{EB} , are noticeably smaller than the field H_K . The maximum applied field for the investigation was set to $H_{max} = \pm 1$ kOe whereas the lowest anisotropy field is ~ 4 kOe. Therefore a correction factor of maximum $\cos \theta \approx 1 - \frac{1}{2} \sin^2 \theta \approx 1 - \frac{1}{2} \frac{1}{16} \bullet c$ is expected where c is a function of H and H_{EB} as well as the angle φ . As such, the maximum correction factor should be in the order of $\sim 1/32$. The real error should be much lower as the linear fit is performed over the whole range of ± 1 kOe.

Inserting Eq. (139), Eq. (158) and Eq. (159) into the second harmonic Hall voltage, Eq. (160), leads to

$$\begin{aligned}
 V_{2\omega} = & -\frac{1}{2}I_{ac} \left(\frac{1}{2}[-\Delta R_A + 2\Delta R_{P\&S} \sin 2\varphi] \right. \\
 & \frac{(H_{Y-EB} + H_{Y-ext}) \sin \varphi + (H_{X-EB} + H_{X-ext}) \cos \varphi}{H_K} \\
 & \frac{\Delta H_Y \sin \varphi + \Delta H_X \cos \varphi}{H_K} + \Delta R_{P\&S} \\
 & \left. \frac{[(H_{Y-EB} + H_{Y-ext}) \sin \varphi + (H_{X-EB} + H_{X-ext}) \cos \varphi]^2}{H_K^2} \right. \\
 & \left. \cos 2\varphi \frac{\Delta H_Y(H_{X-EB} + H_{X-ext}) - \Delta H_X(H_{Y-EB} + H_{Y-ext})}{(H_{X-EB} + H_{X-ext})^2 + (H_{Y-EB} + H_{Y-ext})^2} \right). \quad (161)
 \end{aligned}$$

To shorten the derivation, the following abbreviations have been made in the consecutive computation which read

$$(H_{X-EB} + H_{X-ext}) = a$$

$$(H_{Y-EB} + H_{Y-ext}) = b$$

$$\Delta H_X = c$$

$$\Delta H_Y = d.$$

Eq. (161) now can be re-written as

$$\begin{aligned}
 V_{2\omega} = & -\frac{1}{2}I_{ac} \left(\frac{1}{2}[-\Delta R_A + 2\Delta R_{P\&S} \sin 2\varphi] \frac{b \sin \varphi + a \cos \varphi}{H_K} \right. \\
 & \frac{d \sin \varphi + c \cos \varphi}{H_K} + \Delta R_{P\&S} \frac{[b \sin \varphi + a \cos \varphi]^2}{H_K^2} \\
 & \left. \cos 2\varphi \frac{da - cb}{a^2 + b^2} \right). \quad (162)
 \end{aligned}$$

To insert the angle φ into Eq. (162), the substitutions are firstly inserted into Eq. (140) which are further processed to $\sin \varphi$ and $\cos \varphi$ as

$$\tan \varphi = \frac{H_{Y-EB} + H_{Y-ext}}{H_{X-EB} + H_{X-ext}} = \frac{b}{a}$$

$$\cos \varphi = \frac{1}{\sqrt{1 + \tan^2 \varphi}} = \frac{a}{\sqrt{a^2 + b^2}}$$

$$\sin \varphi = \frac{\tan \varphi}{\sqrt{1 + \tan^2 \varphi}} = \frac{b}{\sqrt{a^2 + b^2}}$$

The functions $\sin 2\varphi$ and $\cos 2\varphi$ are read using the substitutions as

$$\sin 2\varphi = 2 \sin \varphi \cos \varphi = 2 \frac{ab}{a^2 + b^2}$$

$$\cos 2\varphi = \cos^2 \varphi - \sin^2 \varphi = \frac{a^2 - b^2}{a^2 + b^2}.$$

Inserting these expressions into Eq. (162) gives

$$\begin{aligned} V_{2\omega} = & -\frac{1}{2}I_{ac}\left(\frac{1}{2}[-\Delta R_A + 2\Delta R_{P\&S}2\frac{ab}{a^2 + b^2}]\frac{b\frac{b}{\sqrt{a^2+b^2}} + a\frac{a}{\sqrt{a^2+b^2}}}{H_K}\right. \\ & \left.\frac{d\frac{b}{\sqrt{a^2+b^2}} + c\frac{a}{\sqrt{a^2+b^2}}}{H_K} + \Delta R_{P\&S}\frac{[b\frac{b}{\sqrt{a^2+b^2}} + a\frac{a}{\sqrt{a^2+b^2}}]^2}{H_K^2}\right. \\ & \left.\frac{a^2 - b^2}{a^2 + b^2}\frac{da - cb}{a^2 + b^2}\right). \end{aligned} \quad (163)$$

Reformulating leads to

$$\begin{aligned} V_{2\omega} = & -\frac{1}{2}I_{ac}\left(\frac{1}{2}[-\Delta R_A + 2\Delta R_{P\&S}2\frac{ab}{a^2 + b^2}](db + ca)\right. \\ & \left.+ \Delta R_{P\&S}\frac{a^2 - b^2}{a^2 + b^2}(da - cb)\right)\frac{1}{H_K^2}. \end{aligned} \quad (164)$$

Restructuring Eq. (164) in terms of $\Delta R_{P\&S}$ resistance leads to

$$\begin{aligned} V_{2\omega} = & -\frac{1}{2}I_{ac}\left(-\frac{1}{2}\Delta R_A(db + ca)\right. \\ & \left.+ \Delta R_{P\&S}\frac{2ab(db + ca) + (a^2 - b^2)(da - cb)}{a^2 + b^2}\right)\frac{1}{H_K^2}. \end{aligned} \quad (165)$$

The numerator of the coefficient for the $\Delta R_{P\&S}$ can be easily transformed into the form $(a^2 + b^2)(ad + bc)$ which gives

$$V_{2\omega} = -\frac{I_{ac}}{2H_K^2}\left(-\frac{1}{2}\Delta R_A(db + ca) + \Delta R_{P\&S}(ad + bc)\right). \quad (166)$$

Insert the substitutions back leads to

$$\begin{aligned} V_{2\omega} = & \frac{I_{ac}}{2H_K^2}\left(\frac{1}{2}\Delta R_A(\Delta H_Y(H_{Y-EB} + H_{Y-ext}) + \Delta H_X(H_{X-EB}\right. \\ & \left.+ H_{X-ext})) - \Delta R_{P\&S}((H_{X-EB} + H_{X-ext})\Delta H_Y\right. \\ & \left.+ (H_{Y-EB} + H_{Y-ext})\Delta H_X)\right). \end{aligned} \quad (167)$$

In terms of H and H_{EB} where the specific coordinates of the field vectors are re-substituted to $H_{EB} \cos \varphi_E = H_{X-EB}$, $H_{EB} \sin \varphi_E = H_{Y-EB}$, $H \cos \varphi_H = H_{X-ext}$ and $H \sin \varphi_H = H_{Y-ext}$ gives

$$\begin{aligned} V_{2\omega} = & \frac{I_{ac}}{2H_K^2}\left(H\left[\frac{1}{2}\Delta R_A(\Delta H_Y \sin \varphi_H + \Delta H_X \cos \varphi_H)\right.\right. \\ & \left.- \Delta R_{P\&S}(\Delta H_Y \cos \varphi_H + \Delta H_X \sin \varphi_H)\right] \\ & \left.+ H_{EB}[\Delta R_A(\Delta H_Y \sin \varphi_E + \Delta H_X \cos \varphi_E)\right. \\ & \left.- \Delta R_{P\&S}(\Delta H_Y \cos \varphi_E + \Delta H_X \sin \varphi_E)]\right). \end{aligned} \quad (168)$$

Figure 61: First harmonic Hall voltage for (a) the Ta (1.2 nm)/Ru (2 nm) and (b) the Ta (1.4 nm)/Ru (2 nm) sample for applied fields swept at various azimuthal angles. (c) and (d) show the respective field offset versus the azimuthal angle of the applied field for (c) the Ta (1.2 nm)/Ru (2 nm) and (d) the Ta (1.4 nm)/Ru (2 nm). The current density was set to 2×10^{10} A/m².

Finally, the derivative is computed as

$$b_{2\omega} = \frac{\partial V_{2\omega}}{\partial H} = \frac{I_{ac}}{2H_K^2} \left(\Delta H_Y \left(\frac{1}{2} \Delta R_A \sin \varphi_H - \Delta R_{P\&S} \cos \varphi_H \right) + \Delta H_X \left(\frac{1}{2} \Delta R_A \cos \varphi_H - \Delta R_{P\&S} \sin \varphi_H \right) \right). \quad (169)$$

This simple form doesn't contain any information of H_{EB} . Further computation to calculate the SOT effective fields is made in section 5.5.

B.5 FIELD OFFSET FOR RUTHENIUM CAPPING SAMPLE

Here, additional plots for re-sputtered samples are provided with an additional 2 nm of ruthenium capping layer. This is to ensure the in-plane exchange bias field is not related to oxidation or one-time artifacts while fabrication process in the sputtering chamber caused by other target materials creating unique defects in the layers. The first harmonic Hall voltage, V_ω , is shown in Fig. 61 for two samples with same lateral size structures as stated in section 5.2 and various azimuthal angles, φ_H . The film deposition of this set of samples was

made ~ 2 month after the main set of samples as investigated in section 5. As seen from Fig. 61, both samples, Ta (1.2 nm)/Ru (2 nm) sample in (a) and (c) as well as Ta (1.4 nm)/Ru (2 nm) sample in (b) and (d) show in-plane exchange bias fields which confirms that this phenomenon is not related due to oxidation. Also, defects through surrounding gas in the sputtering chamber is unlikely, but has yet to be confirmed by film deposition in a different sputtering chamber with other target compositions and, therefore, different defects from the surrounding gas in the sputtering chamber.

As seen in Fig. 61 (b), an in-plane magnetization loop indicating an in-plane magnetization component is observed, additionally to the in-plane exchange bias field. As the in-plane magnetization loop was observed in one sample only, no further analysis for the in-plane magnetization loop is provided for predominantly magnetization orientation pointing out-of-plane. As seen in Fig. 61 (b), this in-plane magnetization distorts the parabolic function in a non-trivial way. Hence, analysis of simplistic parabolic fitting functions lead to inaccurate predictions. In Fig. 61 (c) and (d) are the respective computed field offsets for (c) Ta (1.2 nm)/Ru (2 nm) and (d) Ta (1.4 nm)/Ru (2 nm) sample. A large field offset of ~ 1000 Oe is observed for the Ta 1.2 sample and ~ 200 Oe for the Ta 1.4 nm sample. However, the plot for the Ta 1.4 sample doesn't exhibit the expected trend and can't be accurately fitted by Eq. (141) which indicates the difficulty in the analysis for this sample. We predict the deposition of Ta 1.4 nm rather corresponds to Ta 1.2 nm that is caused due to the usage of Ta target within a period of two month without any new calibration of the sputtering targets. As such, the sputtering rate might be lowered as compared to the sputtering rate once calibrated two month earlier. The focus to reproduce the field offset with a new set of samples and a different capping layer on top of Ta layer is observed. Hence, the influence from oxidation can be neglected. As the in-plane magnetization component is found in one sample only, we suggest a non-reproducible fabrication artifact, where a decoupling of one layer in the Hall contact branch is caused.

B.6 DISCUSSION ON THE MISMATCH OF φ AND φ_H

As the anisotropy and SOT effective fields are plotted as a function of the applied field, φ_H , here the implications due to this mismatch are discussed with respect to the azimuthal angle of the magnetization in presence of EB-like fields. As shown in chapter 5, the nominal values of the anisotropy and SOT effective fields have been correctly quantified in presence of an EB-like field. However, the azimuthal angles φ and φ_H are not equal in presence of an EB-like field. The offset between angles φ and φ_H can be calculated by Eq. (140) as $\tan \varphi = \frac{H_{EB} \sin \varphi_E + H \sin \varphi_H}{H_{EB} \cos \varphi_E + H \cos \varphi_H}$.

Figure 62: Magnetization azimuthal angle φ as a function of the azimuthal angle of the applied field for (a) the Ta 1.2 nm and (b) the Ta 2.4 nm sample.

To plot the magnetization angle as a function of the applied field angle, the applied field strength has to be approximated as the field is swept within a range of ± 1 kOe. For the Ta 1.2 nm sample with a large offset angle φ_E and **EB**-like field magnitude, the magnetization angle is plotted as a function of the applied field angle using $H = 1$ kOe, as shown in Fig. 62. As a reference, the magnetization angle (φ) is also plotted in case of no **EB**-like field which give $\varphi = \varphi_H$, as shown in Fig. 62 by the red curve.

Small variations are observed which implies a quenching or stretching of the graphs plotted in chapter 5 as a function of the applied field azimuthal angle, φ_H . The corrected anisotropy and **SOT** effective fields as a function of the azimuthal angle of the magnetization vector can be seen in Fig. 63. As expected, minor variations of the azimuthal angles have little impact on the anisotropy and **SOT** field curves. In case the **EB**-like field magnitudes become comparable to the maximum applied field to probe the intrinsic properties, we recommend the corrections to the azimuthal angles as variations might become significant for a reliable quantification of the anisotropy and **SOT** effective fields as a function of the magnetization azimuthal angle.

Figure 63: The corrected anisotropy and SOT effective field plots as a function of the azimuthal angle of the magnetization, ϕ . (a) and (b) show the respective SOT effective fields for (a) Ta 1.2 nm sample and (b) Ta 2.4 nm sample as a function of the magnetization azimuthal angle. (c) and (d) show the respective anisotropy fields, H_K , for (c) Ta 1.2 nm sample and (d) Ta 2.4 nm sample as a function of the magnetization azimuthal angle, ϕ . The current density in the wire was set to 2×10^{10} A/m².

EFFECT OF GEOMETRICAL MODULATION ON PMTJ MAGNETIZATION REVERSAL

First, I introduce the working principle of the object oriented micromagnetic framework (OOMMF) simulation software followed by a motivation part. Subsequently, the simulation results are presented and a summary is given. It should be noted this results using conventional STT as magnetization switching mechanism is comparable with SOT as both torques result in current-induced adiabatic and non-adiabatic STT. The only difference lies in the coefficient which can be converted as explained elsewhere and usually just shifts the results by a factor of ~ 10 to lower current densities for SOT effect [99]. This chapter has been published in **IEEE Transactions on Magnetics** [44].

C.1 OOMMF PRINCIPLES

OOMMF is a project in the Applied and Computational Mathematics Division of the Information Technology Laboratory at the National Institute of Standards and Technology (US), aimed at developing portable, extensible public domain programs and tools for micromagnetics. The official release of the software was in 1998 and over the years the software has been augmented by contributions from various groups working in magnetism. A recent extension module to OOMMF has also been made by Prof. Albert Fert (Nobel Prize Winner Physics 2007) to include the Dzyaloshinskii-Moriya interaction term for the study of Skyrmions. Further information on OOMMF can be obtained from the website: <http://math.nist.gov/oommf/>.

How does OOMMF work?

OOMMF is a micromagnetic software. The length scale of micromagnetics is in the submicrometer range where the atomic structure of the material can be ignored but it is small enough to deliver solutions for DWM or vortices formation. Micromagnetics can be divided in two different problem schemes: one is finding the static micromagnetic equilibrium position of a magnetic system and the second is dynamic micromagnetics for time evolution predictions due to external sources such as an external field. The OOMMF software iteratively computes the minimum energy state of a magnetic system with the given boundary conditions and initial state.

Dynamic micromagnetics

Different from static magnetization configuration where the equilibrium state is obtained by minimizing the total energy equation (2), for dynamic micromagnetics the time evolution of the magnetization is predicted from the influence of external magnetization field. This is described by the LLG equation [Eq. (42)] which is a partial differential equation of time. In case of an external field, the effective field, H_{Eff} , is changed which produces two torques named precession and damping torque as seen in Fig. 16. The solution of the 42 equation is the integral of the derivative. The effective field is connected with the energy through Eq. (1) which reads $\vec{H}_{Eff} = -\frac{1}{\mu_0} \frac{\partial f}{\partial \vec{M}}$. f is the energy density as explained in section 1.1. The average energy density f can be calculated considering Brown's conditions Eqs. (21, 22) [20]. This means that the magnetization should be parallel to the effective field and the magnetization variation perpendicular to its magnetization. The micromagnetic problem is solved on a 2D grid with 3D magnetic spins positioned in the center of every cell. Every cell is a square. Neumann boundary conditions are utilized. The magnetocrystalline anisotropy energy and the Zeeman energy are calculated assuming constant magnetization in each cell. The exchange energy uses the 8 neighbor bilinear interpolation method described in Ref. [38]. The self-magnetostatic (demagnetizing) field is calculated using fast Fourier transform (FFT). We distinguish **ConstMag** where the assumption of a constant magnetization in each cell is used [114], **3dSlab** where in-plane components are calculated with constant offset volume charges and for z-direction constant offset surface charges [10] and **3dCharge** is assuming constant magnetization and surface charges in each cell. The integration of the LLG-equation uses a second order predictor-corrector technique of the Adams type. For every step, the magnetization is renormalized to M_s before calculating the energy and effective fields. The calculation is accepted if the total energy is decreased and the final $\vec{M}$ is smaller than a nominal value. If the step is rejected, the time step size is decreased and calculated again. After acceptance the step size will be adjusted for the next step. Hence, no fixed time steps are predefined. Control points to stop the simulation process are set by indicating a specific time or $\partial \vec{M} / \partial t$ value reached.

Spin-Transfer Torque

The first extension module for STT in OOMMF was written in 2008 by IBM which described the DWM in a nanowire geometry. The partial

differential [LLG](#) equation is used in the form of [Thiaville et al.](#) and [Zhang and Li](#) [177, 151]:

$$\begin{aligned} \frac{d\vec{m}}{dt} = & -|\gamma|\vec{H}_{Eff} \times \vec{m} + \alpha\vec{m} \times \frac{d\vec{m}}{dt} \\ & + u\vec{m} \times \left(\vec{m} \times \frac{\partial\vec{m}}{\partial x} \right) + \beta u\vec{m} \times \frac{\partial\vec{m}}{\partial x} \end{aligned} \quad (170)$$

with $u = \frac{\mu_B g P J}{2e M_s}$, J the current density and P the spin polarization of the current. It should be noted that a positive u value, $u > 0$, reveals an electron flow towards the right direction. The code successfully reproduced experimental results on the [DW](#) dynamics, including the Walker Breakdown whereby the [DW](#) undergo cyclic structural change. You created an [STT](#) extension module for magnetic multilayer structures including exchange biased synthetic antiferromagnetic layer based on the [STT](#) term [171] which was used in this work.

C.2 MOTIVATION

[MRAM](#) is one of the most promising candidates for next-generation non-volatile memory and logic devices owing to its high endurance, fast read/write speed and low power consumption. The basic building block of the [MRAM](#) is the [MTJ](#), wherein an insulator layer is sandwiched between two magnetic layers. The relative orientation between two magnetic layers (parallel/anti-parallel) represents two bits, 0 and 1, which can be read by [TMR](#) effect in [MTJ](#). [STT-MRAM](#) is attractive for replacing the static random access memory ([SRAM](#)) in L2 cache due to its ability for reducing the standby power to nearly zero by exhibiting similar power consumption and processing speed with same size. For [STT-MRAM](#) cells down to 10 nm node size, materials with large [PMA](#) constant are needed. A [PMA](#) material has to satisfy some of the key factors to be employed as a candidate for [STT-MRAM](#). First, the anisotropy constant, K , should be higher so that device can overcome the thermal fluctuations from kBT . Second, the critical current density should be lower to increase the data density. However, these two parameters scale inversely to each other. Different approaches have been introduced in order to minimize the writing power of a perpendicular magnetic anisotropy [MTJ](#) ([pMTJ](#)) such as thermally assisted switching or voltage controlled switching. The aim of this research is to investigate techniques to reduce the switching time and energy of the [MTJ](#) free layer. The research is focused on two major sections, namely; geometrical modulation of device and materials for [STT-MRAM](#), with the ultimate goal of fabricating a [pMTJ](#) device that is able to switch in the sub 10 ns regime with lowest power.

The introduction of geometrical asymmetry in nanostructured [pMTJ](#) may greatly influences the switching speed of the device. Prior to fabricating the [pMTJ](#) structure, micromagnetic simulations have been

conducted to investigate the shape effect on the switching characteristics of pMTJ devices. The shape effect induces an in-plane demagnetizing field which may aid in the switching of devices. This effect is independent of the materials used in the pMTJ stack.

The scaling of current semiconductor based complementary metal-oxide-semiconductor (CMOS) memory technologies is limited by the increased power dissipation due to the increase in standby leakage current as the device size is scaled down. This has led to a renewed interest in investigating alternative cost-effective memory technologies as a replacement for CMOS. Spintronic devices, which utilize both the spin degree of freedom and electrical charge of electron, have been proposed as a strong candidate for universal memory technology. The manipulation of the magnetic state of nanostructure by electrical current has led to a number of spintronics based devices MRAM is one of the most promising candidates for next-generation non-volatile memory and logic devices owing to its high endurance, fast read/write speed and low power consumption. The basic building block of the MRAM is the MTJ, wherein an insulator layer is sandwiched between two magnetic layers. The relative orientation between two magnetic layers (parallel/anti-parallel) represents two bits, '0' and '1', which can be read by TMR effect in MTJ [74, 128]. STT-MRAM is attractive for replacing the SRAM in L2 cache due to its ability for reducing the standby power to nearly zero by exhibiting same processing speed with same size [161, 24]. For STT-MRAM cells down to 10 nm node size, materials with large PMA constant are needed. A PMA material has to satisfy some of the key factors to be employed as a candidate for STT-MRAM. First, a high magnetocrystalline anisotropy constant, K , is required, as it enables scaling while keeping the device immune to thermal fluctuation. For low energy operations, the critical current needed for switching should be small. However, these two parameters scale inversely to each other. Different approaches have been introduced in order to minimize the writing energy of a pMTJ such as thermally assisted switching or voltage controlled switching [58, 32, 42]. As MTJ devices are scaled down for higher densities, the lithographic processes will inherently be reaching their limit. At wafer level, variation in the geometrical shapes of the patterned MTJ devices structure is expected. The minor changes in the aspect ratio and shape of the pMTJ cell would lead to different switching processes. The shape effect has been shown to greatly influence the reversal process in in-plane MTJ structures due to the shape-induced anisotropy. Goggle shape structures have been shown to precisely control the final magnetization configuration to reduce the spread of the switching threshold [118]. Due to the out-of-plane anisotropy in pMTJ, the shape effect is considered negligible. You and Kim have shown that the pMTJ stack with circular shape exhibit a stable out-of-plane vortex configuration, which is an intermediate state between in-plane and out-of-plane

magnetization state [172]. The effect of the in-plane demagnetizing tensor on the reversal process of pMTJ has not been reported to our knowledge.

C.3 SIMULATION SCHEME

In this work, the STT extension tool from You based on the open source project OOMMF was used which focuses on the augmented LLG equation as

$$\begin{aligned} \frac{\partial \vec{m}_f}{\partial t} = & -\gamma \vec{m}_f \times \vec{H}_{Eff} + \alpha \vec{m}_s \times \frac{d\vec{m}_f}{dt} \\ & -\gamma a_J \vec{m}_f \times (\vec{m}_f \times \vec{m}_p) - \gamma b_J (\vec{m}_f \times \vec{m}_p) \end{aligned} \quad (171)$$

where γ is the gyromagnetic ratio, α the Gilbert damping constant, $\vec{H}_{Eff}$ is the effective field, $\vec{m}_{f,p}$ the unit vectors of the magnetization for the ferromagnetic free layer (FL) and ferromagnetic polarizer layer (PL), $a_J = a_1 J$ with $\frac{P\hbar}{2e\mu_0 M_S t}$ and b_J a second order function of the current density J . P is the spin polarization of the PL, $\hbar$ the reduced Planck's constant, e the electron charge, M_S the saturation magnetization of the magnetic layers, μ_0 permeability of vacuum and t the thickness of the FL. The MTJ stack is shown in Fig. 64 (a). The stack comprises (bottom to top) of a field biased synthetic antiferromagnetic layer (SAF), an IL and a FL. The SAF layer comprises of two FM layer separated by a non-magnetic spacer layer. The FM layer next to the IL is termed the PL of the MTJ stack. The use of SAF layer has been shown to reduce the stray field from the PL. To achieve the SAF, the two FM layer comprising the SAF are antiferromagnetically coupled with a two surface exchange energy $\sigma = -1 \times 10^{-3}$ J/m². The lower FM layer of the SAF stack is biased by a field of 4×10^5 A/m. The magnetocrystalline anisotropy constant is assumed to be inversely proportional to the thickness of the FM layer, t , as the interface coupling is decreased. Therefore the thickness of the FL was chosen to be twice the thickness of the PL. The thickness of the FL is chosen to be 2 nm which shows the same trend as a magnetic layer of 2 nm thickness with a buffer layer of about 0.5 nm inserted. The thickness of 1 nm is chosen for all of the other FM layers. All the FM layers have a saturation magnetization M_S of 1.3×10^6 A/m and an exchange stiffness constant $A_{Exch} = 3 \times 10^{-11}$ J/m. The damping constant α was set to 0.01 and the spin polarization P of the PL to $P = 0.7$ to simulate the efficiency of the tunnel junction. The cell mesh size is chosen to be $1 \times 1 \times 1$ nm³ which is smaller than the exchange interaction length. Similar material parameters have been used in literature [72, 173]. The Oersted field generated by the current flowing through the MTJ stack is neglected here.

Figure 64: (a) Schematic of the MTJ stack showing a magnetic free layer FL, an insulator I and a synthetic antiferromagnetic layer SAF consisting of two ferromagnetic layers with a non-magnetic layer NM in between. (b) Cross section of the MTJ stack is shown.

C.4 RESULTS

Magnetocrystalline anisotropy investigations

Three distinct shapes have been studied which are chosen due to their properties as completely symmetric (circular), partial symmetric (elliptical) and asymmetric as a mix between both structures (egg-shape). The top-view of the structures is shown in Fig. 64 (b). The nominal area of the structures investigated is as follows: circular $40 \times 40 \text{ nm}^2$, elliptical $60 \times 40 \text{ nm}^2$ and the asymmetric elliptical (egg-) shape was varied between $45 - 55 \times 40 \text{ nm}^2$.

Firstly, the normalized initial out-of-plane magnetization of the FL was set to +1 and then relaxed until the magnetization reaches its ground state. The normalized magnitude of the out-of-plane magnetization of the magnetic FL as a function of the magnetocrystalline anisotropy constant, K , is presented in Fig. 65 (a). For reference, the normalized magnitude of the out-of-plane magnetization for a single layer with same characteristic as the FL is shown in Fig. 65 (b). The magnetocrystalline anisotropy constant for the FL was varied from 0.5 to 1 MJ/m^3 . As seen in Fig. 65 (a), for the circular pMTJ, as the K value is reduced to 0.67 MJ/m^3 , the relaxed magnetization state adopts an out-of-plane configuration. Below this value, the magnetization adopts a vortex configuration. This confirms results which have been reported before [172]. For egg-shaped structure, we note that a K at 0.9 MJ/m^3 , the magnetization adopts an opposite out-of-plane configuration. As the magnetocrystalline anisotropy, K , is further reduced, the magnetization of the FL adopts an in-plane configuration. For the elliptical structure, the relaxed state adopts an oscillating, positive and negative, out-of-plane configuration, as K is reduced. Below 0.79 MJ/m^3 , the

relaxed state adopts the in-plane configuration until it reaches below the K value of 0.74 MJ/m^3 where the magnetization adopts a vortex configuration. The magnetic configuration of the reference single layer is determined by the competition between the demagnetizing and the magnetocrystalline anisotropy fields. Interestingly, the magnetization changes its out-of-plane direction from out-of-plane antiparallel (AP) to out-of-plane parallel (P) direction for the stack unlike the egg-shape from the single layer which moves in-plane.

For elliptical and egg-shaped structure the single layer magnetization adopts an in-plane configuration at identically the same magnetocrystalline anisotropy constant, K , whereas the circular structure retains its out-of-plane magnetization for even lower K values, as can be seen in Fig. 65 (b). For the MTJ stack, however, the magnetization configuration exhibits a magnetization switch which can be assigned to the stray field from the SAF layer. For in-plane MTJ, the stray field of the SAF layer forms a closed loop which does not affect the magnetic FL [59, 69]. However, this is not the case for a perpendicular SAF layer where the magnetization of the PL affects the FL. For circular shaped MTJ the SAF stabilizes a third state between out-of-plane and in-plane configuration. This state is called vortex state which forms a circular in-plane magnetization around a center with out-of-plane magnetization consistent with previous simulations [172]. The SAF layer prevents the circular FL to fully turn in-plane. Interestingly, for egg-shaped MTJ, the magnetization of the FL switches at the same magnetocrystalline anisotropy as the single layer as seen in Fig. 65 (b). the magnetization changes its out-of-plane direction from out-of-plane AP to out-of-plane P direction for the stack unlike the egg-shape from the single layer which moves in-plane. This phenomenon gives proof that the SAF layer is affecting the FL in pMTJ stack different from in-plane MTJ systems [59, 69]. A further reduction of the magnetocrystalline anisotropy for egg-shaped MTJ also affects the strength of the SAF which reduces its intensity and the magnetization of the FL tilts slowly in-plane. Remarkably, the elliptical shape on the other side shows a pending out-of-plane magnetization between these two shapes dependent on the magnetocrystalline anisotropy, K . This behavior must be related to the partly symmetric structure of the ellipse. The different magnetic states for elliptical shape FL can be seen in Fig. 65 (c).

Figure 65: Relaxed out-of-plane magnetization of the FL for a (a) stack and (b) single layer is shown. The final magnetization direction of the FL is shown in (c) for ellipses with magnetocrystalline anisotropy values of 0.71, 0.76, 0.88 and 0.9 MJ/m^3 .

As for elliptical shape MTJ stack the out-of-plane magnetization, m_z , is transiting between (+/-) out-of-plane magnetization as a function of K . We performed FFT in order to investigate this phenomenon as the stable magnetization precession maybe dependent on the geometry and magnetocrystalline anisotropy. The FFT of the out-of-plane magnetization, m_z , for the relaxation process for different K values can be seen in Fig. 66 (a) and (b) for AP and P configurations respectively. For the AP case the frequencies are distinct with low magnitude of magnetization change. As for the P case, the magnitude of the magnetization significantly increases as the magnetization has to switch from AP to P. The frequencies are therefore lowered with a rather random distribution. This might be related to the symmetry axes and their ratio a/b from minor to major axis a completely different trend is observed. The collective magnetic configuration and stray field within

the system enables the FL to have an out-of-plane magnetization at lower K for circular shape.

Figure 66: Fast Fourier transform of the out-of-plane magnetization for the elliptical FL at two different magnetocrystalline anisotropy values, K .

Current-induced magnetization switching

The current-induced magnetization switching via the spin transfer torque phenomenon was investigated for circular and egg-shaped structures. The initial perpendicular magnetization, m_z , of 0.8 was chosen to introduce a symmetry breaking where the STT from the electrical current can act on the magnetization of the FL. When the magnetization of the PL and FL is aligned strictly P or AP, the STT effect will be non-existent which follows a sine behavior of the out-of-plane magnetization angle according to Eq. (171). To obtain the 0.8 out-of-plane magnetization, m_z , the magnetocrystalline anisotropy values for the circular and egg-shaped structure were 0.6285 MJ/m^3 and 0.9015 MJ/m^3 . The initial state of the MTJ stack is in the AP state. A current pulse of 2 ns was applied along the negative z-direction to both stacks with a current density of $1 \times 10^{11} \text{ J/m}^2$. The pulse duration was chosen to be within the dynamics switching regime and to ensure that the magnetization of the FL switches completely.

Figure 67: Time-dependent out-of-plane magnetization dynamics of the free layer FL for an initial magnetization of $m_z = 0.8$ versus time for various shapes and sizes.

Figure 67 shows the out-of-plane magnetization dynamics of the FL as a function of simulation time. For the circular shape structure, we note that the magnetization switching occurs by a decreasing amplitude oscillatory behavior. The egg-shape structure does not show any oscillation and there is an almost sharp change in magnetization configuration. We observe that the egg-shape switches within 0.45 ns from $m_z = 0.8$ to -0.8 while the circular shape takes around 0.7 ns to switch. Two different dimensions for the circular stack are chosen to compare the effect of magnetic volume on the switching of the FL. The result shows that irrespective of the larger magnetic volume of the egg-shape, the switching is still faster for the same current density applied. This is consistent with the fact that a constant current density is applied which determines the switching time regardless of the cross-sectional area.

Figure 68: Magnetization dynamics for (a) circular-shaped and (b) egg-shaped MTJ.

To gain a better understanding of the reversal process of the FL in circular and egg-shaped structure, we plotted the magnetization

switching as a function of time for the MTJ stack. As seen in Fig. 68 (a), the switching of the circular stack occurs via a precessional motion of the magnetic moments, whereas in the egg-shaped structure Fig. 68 (b) the magnetic moment in the FL does not undergo any oscillation. We have extracted the spin configuration during the switching of pMTJ stacks. For the circular structure, we note that the switching of the FL is via the concentric reversal of the moments starting from the edge of the structure. As such, the switching of the core of the circular device, leads to precessional motion of the spins. For the egg-shaped structure, we note that the reversal occurs from the smaller edge of the structure and propagates towards the larger edge, similar to the propagation of DW as seen in Fig. 69.

Figure 69: (a) Initial magnetization state for the free layer FL of the circular-shaped MTJ. (b) and (c) show intermediate magnetization states for the current-induced magnetization switching. (d)-(f) Magnetization states for the FL of the egg-shaped MTJs, respectively. The color code represents the out-of-plane magnetization where blue indicates the antiparallel state with $+z$ -axis magnetization and red indicates the parallel state with $-z$ -axis magnetization.

To investigate the change of magnetization in further detail we plotted the respective energies which are proportional to the magnetic fields. Figure 70 (a) and (c) show the time dependency of the exchange, uniaxial and demagnetization energy for a current density, J , of 1×10^{11} A/m². The energy fluctuations for exchange, uniaxial and demagnetization energies of the circular structure are on similar order of magnitudes and interact with each other which lead to different oscillations. This is further exemplified in the FFT plot shown in Fig. 70 (b). The demagnetizing energy change stands in contrary to the uniaxial and exchange energies. The exchange energy oscillates at specific frequencies whereas uniaxial and demagnetization energies change over a broader frequency range. This might be due to

the vortex state exhibited by the circular structure at the beginning. Interestingly, the exchange energy of egg-shaped structure drops to nearly zero as shown in Fig. 70 (c). This can be explained by the fact that the initial state of the egg-shaped structure has nearly parallel magnetic moments with $m_z = 0.8$ out-of-plane magnetization which minimizes the exchange energy close to zero. Therefore the uniaxial anisotropy energy increases until the magnetization is in-plane and drops again to a minimum when the magnetization is perpendicular again. The demagnetization energy drops at the beginning in the same way until the magnetization reaches the in-plane configuration and increases afterwards. Figure 70 (d) depicts the FFT for egg-shape structure. No induced frequency spectrum is observed which suggests that exchange energy is responsible for the oscillations.

Figure 70: (a) and (c) Time dependence for exchange, uniaxial, and demagnetizing energy for (a) circular structure and (c) egg-shaped structure for a current density of 1×10^{11} A/m². (b) and (d) Corresponding frequency dependence for exchange, uniaxial and demagnetizing energy for (b) circular structure and (d) egg-shaped structure.

Figure 71 reveals the switching time dependence on the current density from AP to P state. We obtain for same current densities lower switching times for the egg-shape than for the circular shape structure for $m_z = 0.8$. For a low current density J of 0.5×10^{11} A/m² the switching time can be reduced by 47 %. In terms of reducing power consumption this reduction is remarkable because the egg-shape structure exhibits a larger K value which leads to a higher

current density. The switching time τ for the magnetization from $m_z = 0.8$ to -0.8 is given by the following trend as [147]:

$$\tau \propto \frac{1}{\alpha J} \ln \frac{\theta}{\theta_0}, \quad (172)$$

where θ and θ_0 are the final and initial magnetization with respect to the z-direction. For the switching time we kept the initial and final magnetization to $m_z = 0.8$ which is constant here. The inversely proportional trend from the current density to the switching time can be clearly seen in Fig. 71.

Figure 71: Switching time depending on the current density for circular and egg-shaped MTJs with initial perpendicular magnetization $m_z = 0.8$ and magnetocrystalline anisotropy of 1×10^6 J/m³.

The demagnetizing field is the main difference between the two structures. It should be noted that the effective field here is also not the same for circular and egg-shape MTJ because it includes the magnetocrystalline anisotropy and the external magnetic effects. The stray field from the PL can be conceived as external magnetization field which is different for the two structures.

Demagnetizing field investigation

For a symmetric structure as the circular shape, the demagnetizing field is inside the plane and normal to the edges. The demagnetizing field can be written as

$$\vec{H}_{Dem} = (4\pi \vec{M} t y_0) \int_{-\infty}^{\infty} \frac{dx}{r^3}, \quad (173)$$

with t the thickness, y_0 the distance from the edge to the middle point and r the distance of the position to the middle point of the structure. The magnitude can be expressed by $H_{Dem} = \frac{8\pi M_S t}{y_0}$ [148]. For a more

complex structure such as the elliptical or egg-shape structure, the demagnetizing field has to be calculated analytically. It can be noted similar to the end of a bar magnet that the edge poles are situated at the edges of the long axis. For the egg-shape structure this is even more complicated because the long axis is not symmetrical which results in a disparate ratio of magnetic flux at the edge poles with a higher magnetic flux at the narrower edge. For any given geometry, the demagnetizing field is given by

$$\vec{H}_{Dem} = N\vec{M}, \quad (174)$$

with N the demagnetizing factor. The demagnetizing factor is a sum of the demagnetizing factors per coordinate (x, y, z) $N = N_x + N_y + N_z$. For elliptical shape we can obtain [148]

$$N_x = \frac{\pi t}{4a} \left[1 - \frac{1}{4} \frac{a-b}{a} - \frac{3}{16} \left(\frac{a-b}{a} \right)^2 \right], \quad (175)$$

$$N_y = \frac{\pi t}{4a} \left[1 + \frac{5}{4} \frac{a-b}{a} + \frac{21}{16} \left(\frac{a-b}{a} \right)^2 \right], \quad (176)$$

$$N_z = 1 - N_x - N_y. \quad (177)$$

Factors a and b are the major and minor axis of the ellipse, respectively. For our ellipse with $t = 2$ nm, $a = 60$ nm and $b = 40$ nm we obtain $N_x = \frac{\pi}{120} \frac{43}{48}$, $N_y = \frac{\pi}{120} \frac{77}{48}$ and $N_z = 1 - \frac{\pi}{48}$. The demagnetizing factor N_z becomes close to 1 much larger than the other two as expected for a very thin magnetization structures. Also, the fabrication of this structure is relatively simple. Unfortunately, this advantage is suspended if circular and egg-shape structures are compared with a high K value of 1 MJ/m^3 . This underlines the importance of the initial spin configuration. The larger switching time can be explained by a lower torque which acts on the in-plane magnetization. For nearly perpendicular magnetization for $K = 1 \text{ MJ/m}^3$ the initial torque is close to zero and starts growing with increased in-plane magnetization.

Investigation of material parameters on critical switching current

The investigation of the current induced magnetization switching in relation to the material parameters is of great interest for the successful implementation into devices. The critical switching current density is given by the following relation [161, 134] :

$$J_c = \frac{2e\alpha M_S H_{Eff} t}{\hbar P}, \quad (178)$$

with $H_{Eff} = H_E + H_{An} + A_{Exch} k^2 + H_{Dem}$, where H_E is the interlayer exchange field, $H_{An} = \frac{2K}{M_S}$ the anisotropy field, k the spin wave vector

and H_{Dem} denotes for the out-of-plane demagnetizing field.

The switching behavior of the asymmetric structure, egg-shaped, was investigated as a function of the exchange stiffness constant. The critical current density as a function of the exchange stiffness constant is shown in Fig. 72. The time for this magnetization reversal process from AP to P state has been fixed to 2 ns for a magnetization change of $m_z = 0.8$ to -0.8 .

Figure 72: Switching current as a function of the exchange constant of the FL for the egg-shaped structure with a unit magnetization $m_z = 0.8$ to $m_z = -0.8$, a uniaxial constant K of $0.9015 \times 10^6 \text{ J/m}^3$ and a switching time of 2 ns.

The critical current density in a range of 1.25 to $2.25 \times 10^{-11} \text{ J/m}$ from the exchange stiffness constant increases stepwise with a nearly constant current density above. The step can be explained due to an additional spin wave within the fixed time of 2 ns. The decrease in current density from exchange constants 2.25 to $4.00 \times 10^{-11} \text{ J/m}$ cannot be explained by Eq. (178) and must be attributed to the fixed simulation time. For the simulated structure an exchange constant of $3.00 \times 10^{-11} \text{ J/m}$ has been used which corresponds to a relatively stable current density of around $0.216 \times 10^{11} \text{ A/m}^2$.

The damping constant α is also of great importance for the switching behavior as seen from Eq. (172) as well as from Eq. (178). A linear relationship is therefore expected for the critical current density as a function of the damping constant.

Figure 73: Switching current as a function of the damping constant of the FL for the egg-shaped structure with a unit magnetization $m_z = 0.8$ to $m_z = -0.8$, a uniaxial constant K of $0.9015 \times 10^6 \text{ J/m}^3$ and a switching time of 2 ns.

In a range of 0.03 to 0.2 of the damping constant, a linear trend of the critical current density is observed. However at lower damping constant, an unexpected increase in current density is discovered. The fixed time leads to an artifact for low damping constant where the state of the spin wave is more crucial compared to larger damping constant. The saturation magnetization is an intrinsic property of the material which can be altered through the fabrication process. The behavior of critical performance characteristics such as the magnetization dynamics as a function of the saturation magnetization is of crucial interest for an engineering integration into practical device architecture. The critical magnetization switching current density as a function of the saturation magnetization is shown in Fig. 74

Figure 74: Switching current as a function of the saturation magnetization M_s of the FL for the egg-shaped structure with a unit magnetization $m_z = 0.8$ to $m_z = -0.8$, a uniaxial constant K of $0.9015 \times 10^6 \text{ J/m}^3$ and a switching time of 2 ns.

The critical current density first decreases as a function of saturation magnetization with a minimum at $0.161 \times 10^{11} \text{ A/m}^2$ for a saturation magnetization of $1.2 \times 10^6 \text{ A/m}$, and increases for larger saturation magnetization. The decrease in current density from 0.235 to $0.161 \times 10^{11} \text{ A/m}^2$ cannot be explained by the anisotropy field decrease with increasing saturation magnetization. We rather believe that due to the lateral structure spin waves are induced which lower the current density with increasing saturation magnetization. The maximum number of spin waves should be denoted at the saturation magnetization with the lowest critical current density. For saturation magnetization larger than $1.2 \times 10^6 \text{ A/m}$, an increase in current density is observed as expected from Eq. (178).

C.5 SUMMARY

In summary we have performed micromagnetic simulations on representative pMTJ stacks with circular, elliptical and egg-shaped cross section, to mimic the different lateral deformations. The results show that lateral defects greatly influence the magnetic stability. This leads to requiring larger perpendicular magnetocrystalline anisotropy to sustain the same magnetization state as the circular structures. This can be explained by the symmetry breaking induced by the lateral defect in the MTJ.

BIBLIOGRAPHY

- [1] A. Aharoni. *Introduction to the Theory of Ferromagnetism*. Oxford University Press., 2001.
- [2] V. P. Amin and M. D. Stiles. Spin transport at interfaces with spin-orbit coupling: Formalism. *Phys. Rev. B*, 94:104419, 2016. URL <https://doi.org/10.1103/PhysRevB.94.104419>.
- [3] P. K. Amiri, Z. M. Zeng, J. Langer, H. Zhao, G. Rowlands, Y.-J. Chen, I. N. Krivorotov, J. P. Wang, H. W. Jiang, J. A. Katine, Y. Huai, K. Galatsis, and K. L. Wang. Switching current reduction using perpendicular anisotropy in CoFeB-MgO magnetic tunnel junctions. *Appl. Phys. Lett.*, 98:112507, 2011. URL <http://dx.doi.org/10.1063/1.3567780>.
- [4] C. O. Avci, K. Garello, M. Gabureac, A. Ghosh, A. Fuhrer, S. F. Alvarado, and P. Gambardella. Interplay of spin-orbit torque and thermoelectric effects in ferromagnet/normal-metal bilayers. *Phys. Rev. B*, 90:224427, 2014. URL <https://doi.org/10.1103/PhysRevB.90.224427>.
- [5] C. O. Avci, K. Garello, A. Ghosh, M. Gabureac, S. F. Alvarado, and P. Gambardella. Unidirectional spin Hall magnetoresistance in ferromagnet/normal metal bilayers. *Nat. Phys.*, 11:570–575, 2015. URL <https://www.nature.com/articles/nphys3356>.
- [6] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazeles. Giant magnetoresistance of (001)fe/(001)cr magnetic superlattices. *Phys. Rev. Lett.*, 61:2472, 1988. URL <https://doi.org/10.1103/PhysRevLett.61.2472>.
- [7] L. Berger. Side-Jump Mechanism for the Hall Effect of Ferromagnets. *Phys. Rev. B*, 2:4559–4566, 1970. URL <https://journals.aps.org/prb/abstract/10.1103/PhysRevB.2.4559>.
- [8] L. Berger. Exchange interaction between ferromagnetic domain wall and electric current in very thin metallic films. *J. Appl. Phys.*, 55:1954, 1984. URL <http://dx.doi.org/10.1063/1.333530>.
- [9] L. Berger. Emission of spin waves by a magnetic multilayer traversed by a current. *Phys. Rev. B*, 54:9353–9358, 1996. URL <https://journals.aps.org/prb/abstract/10.1103/PhysRevB.54.9353>.

- [10] D. V. Berkov, K. Ramstöck, and A. Hubert. Solving Micromagnetic Problems. Towards an Optimal Numerical Method. *Phys. Stat. Sol. (a)*, 137:207, 1993. URL <http://onlinelibrary.wiley.com/doi/10.1002/pssa.2211370118/full>.
- [11] M. V. Berry. Quantal phase factors accompanying adiabatic changes. *Proceedings of the Royal Society A*, 392:45–57, 1984. URL <http://rspa.royalsocietypublishing.org/content/392/1802/45>.
- [12] D. Bhowmik, M. E. Nowakowski, L. You, O. Lee, D. Keating, M. Wong, J. Bokor, and S. Salahuddin. Deterministic Domain Wall Motion Orthogonal To Current Flow Due To Spin Orbit Torque. *Sci. Rep.*, 5:11823, 2015. URL <https://www.nature.com/articles/srep11823>.
- [13] G. Binasch, P. Grünberg, F. Sauererbach, and W. Zinn. Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange. *Phys. Rev. B*, 39:4828(R), 1989. URL <https://doi.org/10.1103/PhysRevB.39.4828>.
- [14] S. Blundell. *Magnetism in Condensed Matter*. Oxford University Press Inc., New York, 2009.
- [15] A. Bollero, L. D. Buda-Prejbeanu, V. Baltz, J. Sort, B. Rodmacq, and B. Dieny. Magnetic behavior of systems composed of coupled ferromagnetic bilayers with distinct anisotropy directions. *Phys. Rev. B*, 73:144407, 2006. URL <https://doi.org/10.1103/PhysRevB.73.144407>.
- [16] A. Bollero, V. Baltz, L. D. Buda-Prejbeanu, B. Rodmacq, and B. Dieny. Origin and control of exchange-bias-like phenomenon in coupled ferromagnetic [Pt/Co]/NiFe bilayers. *Phys. Rev. B*, 84:094423, 2011. URL <https://doi.org/10.1103/PhysRevB.84.094423>.
- [17] W. Borders, S. Fukami, and H. Ohno. Stack Structure Dependence of Magnetic Properties of PtMn/[Co/Ni] Films for Spin-Orbit Torque Switching Device. *IEEE Trans. Magn.*, doi: 10.1109/TMAG.2017.2703817, 2017. URL <http://ieeexplore.ieee.org/abstract/document/7926446>.
- [18] O. Boulle, J. Kimling, P. Warnicke, M. Kläui, U. Rüdiger, G. Malinowski, H. J. M. Swagten, B. Koopmans, C. Ulysse, and G. Fani. Nonadiabatic Spin Transfer Torque in High Anisotropy Magnetic Nanowires with Narrow Domain Walls. *Phys. Rev. Lett.*, 101: 216601, 2008. URL <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.101.216601>.

- [19] S. Brivio, C. Rinaldi, D. Petti, R. Bertacco, and F. Sanchez. Epitaxial growth of Fe/BaTiO₃ heterostructures. *Thin Solid Films*, 88: 5804–5807, 2011. URL <https://doi.org/10.1016/j.tsf.2010.12.193>.
- [20] J. W. F. Brown. *Micromagnetics*. Krieger, New York, 1978.
- [21] K. Cai, M. Yang, H. Ju, S. Wang, Y. Ji, B. Li, K. W. Edmonds, Y. Sheng, B. Zhang, N. Zhang, S. Liu, H. Zheng, and K. Wang. Electric field control of deterministic current-induced magnetization switching in a hybrid ferromagnetic/ferroelectric structure. *Nat. Mater.*, 16:712–716, 2017. URL <https://www.nature.com/nmat/journal/v16/n7/full/nmat4886.html>.
- [22] W. C. Cain and M. H. Kryder. Investigation of the exchange mechanism in NiFe-TbCo bilayers. *J. Appl. Phys.*, 67:5722–5724, 1990. URL <http://dx.doi.org/10.1063/1.346107>.
- [23] P. F. Carcia, A. D. Meinhaldt, and A. Suna. Perpendicular magnetic anisotropy inPd/Co thin film layered structures. *Appl. Phys. Lett.*, 47:178–180, 1985. URL <http://aip.scitation.org/doi/abs/10.1063/1.96254>.
- [24] E. Chen, D. Apalkov, Z. Diao, A. Driskill-Smith, D. Druist, D. Lottis, V. Nikitin, X. Tang, S. Watts, S. Wang, S. A. Wolf, A. W. Ghosh, J. W. Lu, S. J. Poon, M. Stan, W. H. Butler, S. Gupta, C. K. A. Mewes, T. Mewes, and P. B. Visscher. Advances and future prospects of spin-transfer torque random access memory. *IEEE Trans. Magn.*, 46:1873–1878, 2010. URL <http://ieeexplore.ieee.org/document/5467394/>.
- [25] G. Chen, T. Ma, A. T. N’Diaye, H. Kwon, C. Won, Y. Wu, and A. K. Schmid. Tailoring the chirality of magnetic domain walls by interface engineering. *Nat. Commun.*, 4:2671, 2013. URL <https://www.nature.com/articles/ncomms3671>.
- [26] W. Chen, M. Sigrist, J. Sinova, and D. Manske. Minimal Model of Spin-Transfer Torque and Spin Pumping caused by the Spin Hall Effect. *Phys. Rev. Lett.*, 115:217203, 2015. URL <https://doi.org/10.1103/PhysRevLett.115.217203>.
- [27] W. Chen, M. Sigrist, and D. Manske. Spin Hall effect induced spin transfer through an insulator. *Phys. Rev. B*, 94:104412, 2016. URL <https://doi.org/10.1103/PhysRevB.94.104412>.
- [28] Y. Chen, H. Celik, T. Wang, H. Kannan, I. N. Krivorotov, and J. Q. Xiao. Quantifying angular dependence of spin-orbit torques in Ta/CoFeB/MgO trilayers with perpendicular magnetic anisotropy. *Phys. Rev. B*, 95:144405, 2017. URL <https://doi.org/10.1103/PhysRevB.95.144405>.

- [29] Y.-T. Chen, S. Takahashi, H. Nakayama, M. Althammer, S. T. B. Goennenwein, E. Saitoh, and G. E. W. Bauer. Theory of spin Hall magnetoresistance. *Phys. Rev. B*, 87:144411, 2013. URL <https://doi.org/10.1103/PhysRevB.87.144411>.
- [30] Y.-T. Chen, S. Takahashi, H. Nakayama, M. Althammer, T. B. Goennenwein, E. Saitoh, and G. E. W. Bauer. Theory of spin Hall magnetoresistance (SMR) and related phenomena. *J. Phys.:Cond. Matt.*, 28:103004, 2016. URL <http://iopscience.iop.org/article/10.1088/0953-8984/28/10/103004/meta>.
- [31] A. Chernyshov, M. Overby, X. Liu, J. K. Furdyna, Y. Lyanda-Geller, and P. Rokhinson. Evidence for reversible control of magnetization in a ferromagnetic material by means of spin-orbit magnetic field. *Nat. Phys.*, 5:656–659, 2009. URL <http://www.nature.com/nphys/journal/v5/n9/full/nphys1362.html>.
- [32] D. Chiba, S. Fukami, K. Shimamura, N. Ishiwata, K. Kobayashi, and T. Ono. Electrical control of the ferromagnetic phase transition on cobalt at room temperature. *Nat. Mater.*, 10:853–856, 2011. URL <https://www.nature.com/nmat/journal/v10/n11/full/nmat3130.html>.
- [33] S. Chikazumi. *Physics of Ferromagnetism*. Oxford University Press., 1997.
- [34] M. Cubukcu, O. Boulle, M. Drouard, K. Garello, C. O. Avci, I. M. Miron, J. Langer, B. Ocker, P. Gambardella, and G. Gaudin. Spin-orbit torque magnetization switching of a three-terminal perpendicular magnetic tunnel junction. *Appl. Phys. Lett.*, 104:042406, 2014. URL <http://dx.doi.org/10.1063/1.4863407>.
- [35] G. H. O. Daalderop, P. J. Kelly, and F. J. A. den Broeder. Prediction and confirmation of perpendicular magnetic anisotropy in Co/Ni multilayers. *Phys. Rev. Lett.*, 68:682–685, 1992. URL <https://doi.org/10.1103/PhysRevLett.68.682>.
- [36] J. M. Daughton. GMR applications. *J. Magn. Magn. Mater.*, 192:334–342, 1999. URL [https://doi.org/10.1016/S0304-8853\(98\)00376-X](https://doi.org/10.1016/S0304-8853(98)00376-X).
- [37] K. Di, V. L. Zhang, H. S. Lim, S. C. Ng, M. H. Kuok, J. Wu, J. Yoon, X. Qiu, and H. Yang. Direct Observation of the Dzyaloshinskii-Moriya Interaction in a Pt/Co/Ni Film. *Phys. Rev. Lett.*, 114:047201, 2015. URL <https://doi.org/10.1103/PhysRevLett.114.047201>.
- [38] M. J. Donahue and R. D. McMichael. Exchange energy representations in computational micromagnetics. *Physica B*, 233:272–278, 1997. URL [https://doi.org/10.1016/S0921-4526\(97\)00310-4](https://doi.org/10.1016/S0921-4526(97)00310-4).

- [39] M. I. Dyakonov. Magnetoresistance due to Edge Spin Accumulation. *Phys. Rev. Lett.*, 99:126601, 2007. URL <https://doi.org/10.1103/PhysRevLett.99.126601>.
- [40] M. I. Dyakonov and V. I. Perel. Current-induced spin orientation of electrons in semiconductors. *Phys. Lett. A*, 35:459–460, 1971. URL <http://www.sciencedirect.com/science/article/pii/0375960171901964>.
- [41] S. Emori, U. Bauer, S.-M. Ahn, E. Martinez, and G. S. D. Beach. Current-driven dynamics of chiral ferromagnetic domain walls. *Nat. Mater.*, 12:611–616, 2013. URL <http://www.nature.com/nmat/journal/v12/n7/abs/nmat3675.html>.
- [42] M. Endo, S. Kanai, S. Ikeda, F. Matsukura, and H. Ohno. Electric-field effects on thickness dependent magnetic anisotropy of sputtered MgO/Co₄₀Fe₄₀B₂₀/Ta structures. *Appl. Phys. Lett.*, 96:212503, 2010. URL <http://dx.doi.org/10.1063/1.3429592>.
- [43] C. Engel, S. Goolaup, F. Luo, W. Gan, and W. S. Lew. Spin-orbit torque induced magnetization anisotropy modulation in Pt/(Co/Ni)₄/Co/IrMn heterostructure. *J. Appl. Phys.*, 121:143902, 2017. URL <http://dx.doi.org/10.1063/1.4980108>.
- [44] C. Engel, S. Goolaup, F. Luo, and W. S. Lew. Quantitative characterization of spin-orbit torques in Pt/Co/Pt/Co/-Ta/BTO heterostructures due to the magnetization azimuthal angle dependence. *Phys. Rev. B*, 96:054407, 2017. URL <https://doi.org/10.1103/PhysRevB.96.054407>.
- [45] C. Engel, S. Goolaup, F. Luo, and W. S. Lew. Characterizing angular dependence of spin-orbit torque effective fields in Pt/(Co/Ni)₂/Co/IrMn structure. *IEEE Trans. Magn.*, 53:1400604, 2017. URL <https://ieeexplore.ieee.org/abstract/document/7929382/>.
- [46] P. R. Evans, G. Yi, and W. Schwarzacher. Current perpendicular to plane giant magnetoresistance of multilayered nanowires electrodeposited in anodic aluminium oxide membranes. *Appl. Phys. Lett.*, 76:481, 2000. URL <http://dx.doi.org/10.1063/1.125794>.
- [47] P. R. Evans, G. Yi, and W. Schwarzacher. Spin-polarized current induced switching in Co/Cu/Co pillars. *Appl. Phys. Lett.*, 78:3663, 2001. URL <http://dx.doi.org/10.1063/1.1374230>.
- [48] X. Fan, J. Wu, Y. Chen, M. J. Jerry, H. Zhang, and J. Q. Xiao. Quantifying interface and bulk contributions to spin-orbit torque in magnetic bilayers. *Nat. Commun.*, 5:3042, 2014. URL <https://www.nature.com/articles/ncomms4042>.

- [49] D. Fang, H. Kurebayashi, J. Wunderlich, K. Výborný, L. P. Zârbo, R. P. Campion, A. Casiraghi, B. L. Gallagher, T. Jungwirth, and A. J. Ferguson. Spin-orbit-driven ferromagnetic resonance. *Nat. Nanotechnol.*, 6:413–417, 2011. URL <https://www.nature.com/nnano/journal/v6/n7/full/nnano.2011.68.html>.
- [50] A. Fert. Nobel Lecture: Origin, development, and future of spintronics. *Rev. Mod. Phys.*, 89:1517–1530, 2008. URL <https://doi.org/10.1103/RevModPhys.80.1517>.
- [51] A. Fert, V. Cros, and J. Sampaio. Skyrmions on the track. *Nat. Nanotechnol.*, 8:152–156, 2013. URL <https://www.nature.com/nnano/journal/v8/n3/full/nnano.2013.29.html>.
- [52] S. Fukami, C. Zhang, S. DuttaGupta, A. Kurenkov, and H. Ohno. Magnetization switching by spin-orbit torque in an antiferromagnet/ferromagnet bilayer system. *Nat. Mater.*, 15:535–541, 2016. URL <http://www.nature.com/nmat/journal/v15/n5/full/nmat4566.html>.
- [53] K. Garello, I. M. Miron, C. O. Avci, F. Freimuth, Y. Mokrousov, S. Blügel, S. Auffret, O. Boulle, G. Gaudin, and P. Gambardella. Symmetry and magnitude of spin-orbit torques in ferromagnetic heterostructures. *Nat. Nanotechnol.*, 8:587–593, 2013. URL <https://www.nature.com/nmat/journal/v14/n9/full/nmat4360.html>.
- [54] A. Ghosh, K. Garello, C. O. Avci, M. Gabureauc, and P. Gambardella. Interface-enhanced spin-orbit torques and current-induced magnetization switching of pd/co/alox layers. *Phys. Rev. Appl.*, 7:014004, 2017. URL <https://doi.org/10.1103/PhysRevApplied.7.014004>.
- [55] M. Gruyters and D. Riegel. Strong exchange bias by a single layer of independent antiferromagnetic grains: The CoO/Co model system. *Phys. Rev. B*, 63:052401, 2000. URL <https://doi.org/10.1103/PhysRevB.63.052401>.
- [56] P. P. J. Haazen, E. Murè, J. H. Franken, R. Lavrijsen, H. J. M. Swagten, and B. Koopmans. Domain wall depinning governed by the spin Hall effect. *Nat. Mater.*, 12:299–303, 2013. URL <http://www.nature.com/nmat/journal/v12/n4/full/nmat3553.html>.
- [57] P. M. Haney, H.-W. Lee, K.-J. Lee, A. Manchon, and M. D. Stiles. Current induced torques and interfacial spin-orbit coupling: Semiclassical modeling. *Phys. Rev. B*, 87:174411, 2013. URL <https://doi.org/10.1103/PhysRevB.87.174411>.

- [58] M. Hatami, G. E. W. Bauer, Q. Zhang, and P. J. Kelly. Thermal spin-transfer torque in magnetoelectronic devices. *Phys. Rev. Lett.*, 99:066603, 2007. URL <https://doi.org/10.1103/PhysRevLett.99.066603>.
- [59] J. Hayakawa, S. Ikeda, K. Miura, M. Yamanouchi, Y. M. Lee, R. Sasaki, M. Ichimura, K. Ito, T. Kawahara, R. Takemura, T. Meguro, F. Matsuka, H. Takahashi, H. Matsuoka, and H. Ohno. Current-Induced Magnetization Switching in MgO Barrier Magnetic Tunnel Junctions with CoFeB-Based Synthetic Ferrimagnetic Free Layers. *IEEE Trans. Magn.*, 44:1962–1967, 2008. URL <http://ieeexplore.ieee.org/abstract/document/4544915/>.
- [60] M. Hayashi, L. Thomas, C. Rettner, R. Moriya, X. Jiang, and S. S. P. Parkin. Dependence of Current and Field Driven Depinning of Domain Walls on Their Structure and Chirality in Permalloy Nanowires. *Phys. Rev. Lett.*, 97:207205, 2006. URL <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.97.207205>.
- [61] M. Hayashi, J. Kim, M. Yamanouchi, and H. Ohno. Quantitative characterization of the spin-orbit torque using harmonic Hall voltage measurements. *Phys. Rev. B*, 89:144425, 2014. URL <https://journals.aps.org/prb/abstract/10.1103/PhysRevB.89.144425>.
- [62] J. Heinen, O. Boulle, K. Rousseau, G. Malinowski, M. Kläui, H. J. M. Swagten, B. Koopmans, C. Ulysse, and G. Faini. Current-induced domain wall motion in Co/Pt nanowires: Separating spin torque and Oersted-field effects. *Appl. Phys. Lett.*, 96:202510, 2010. URL <http://dx.doi.org/10.1063/1.3405712>.
- [63] J. E. Hirsch. Spin Hall Effect. *Phys. Rev. Lett.*, 83:1834–1837, 1999. URL <https://doi.org/10.1103/PhysRevLett.83.1834>.
- [64] S. Y. Hsu, A. Barthélémy, P. Holody, R. Loloee, P. A. Schroeder, and A. Fert. Towards a Unified Picture of Spin Dependent Transport in and Perpendicular Giant Magnetoresistance and Bulk Alloys. *Phys. Rev. Lett.*, 78:2652, 1997. URL <https://doi.org/10.1103/PhysRevLett.78.2652>.
- [65] S. Y. Huang, X. Fan, D. Qu, Y. P. Chen, W. G. Wang, J. Wu, T. Y. Chen, J. Q. Xiao, and C. L. Chien. Transport Magnetic Proximity Effects in Platinum. *Phys. Rev. Lett.*, 109:107204, 2012. URL <https://doi.org/10.1103/PhysRevLett.109.107204>.
- [66] A. Hubert and R. Schäfer. *Magnetic Domains. The Analysis of Magnetic Microstructures*. Springer, Berlin, 2000.

- [67] S. Ikeda, K. Miura, H. Yamamoto, K. Mizunuma, H. D. Gan, M. Endo, J. Kanai, S. Hayakawa, F. Matsukura, and H. Ohno. A perpendicular-anisotropy CoFeB-MgO magnetic tunnel junction. *Nat. Mater.*, 9:721–724, 2010. URL <http://www.nature.com/nmat/journal/v9/n9/full/nmat2804.html>.
- [68] J. Inoue and S. Maekawa. Theory of tunneling magnetoresistance in granular magnetic films. *Phys. Rev. B*, 53:R11927(R), 1996. URL <https://doi.org/10.1103/PhysRevB.53.R11927>.
- [69] W. C. Jeong, J. H. Park, G. H. Koh, G. T. Jeong, H. S. Jeong, and K. Kim. Switching field distribution in magnetic tunnel junctions with a synthetic antiferromagnetic free layer. *J. Appl. Phys.*, 97:10C905, 2005. URL <http://dx.doi.org/10.1063/1.1846558>.
- [70] M. Johnson and R. H. Silsbee. Interfacial charge-spin coupling: Injection and detection of spin magnetization in metals. *Phys. Rev. Lett.*, 55:1790–1793, 1985. URL <https://doi.org/10.1103/PhysRevLett.55.1790>.
- [71] M. Julliere. Tunneling between ferromagnetic films. *Phys. Lett. A*, 54:225–226, 1975. URL [https://doi.org/10.1016/0375-9601\(75\)90174-7](https://doi.org/10.1016/0375-9601(75)90174-7).
- [72] M. H. Jung, S. Park, C.-Y. You, and S. Yuasa. Bias dependence of in-plane and out-of-plane spin-transfer torques in symmetric MgO-based magnetic tunnel junctions. *Phys. Rev. B*, 81:134419, 2010. URL <https://doi.org/10.1103/PhysRevB.81.134419>.
- [73] R. Karplus and J. M. Luttinger. Hall Effect in Ferromagnetics. *Phys. Rev. B*, 95:1154–1160, 1954. URL <https://journals.aps.org/pr/abstract/10.1103/PhysRev.95.1154>.
- [74] J. Katine, F. J. Albert, R. A. Buhrmann, E. B. Myers, and D. C. Ralph. Current-Driven Magnetization Reversal and Spin-Wave Excitations in Co/Cu/Co Pillars. *Phys. Rev. Lett.*, 84:3149–3152, 2000. URL <https://doi.org/10.1103/PhysRevLett.84.3149>.
- [75] Y. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom. Coherent spin manipulation without magnetic fields in strained semiconductors. *Nature*, 427:50–53, 2004. URL <http://www.nature.com/nature/journal/v427/n6969/abs/nature02202.html>.
- [76] J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, and H. Ohno. Layer thickness dependence of the current-induced effective field vector in Ta|CoFeB|MgO. *Nat. Mater.*, 12:240–245, 2013. URL <http://www.nature.com/nmat/journal/v12/n3/abs/nmat3522.html>.

- [77] J. Kim, P. Sheng, S. Takahashi, S. Mitani, and M. Hayashi. Spin Hall Magnetoresistance in Metallic Bilayers. *Phys. Rev. Lett.*, 116:097201, 2016. URL <https://doi.org/10.1103/PhysRevLett.116.097201>.
- [78] C. Kittel. Theory of the Structure of Ferromagnetic Domains in Films and Small Particles. *Phys. Rev.*, 70:965, 1946. URL <https://doi.org/10.1103/PhysRev.70.965>.
- [79] W. J. Kong, Y. R. Ji, X. Zhang, H. Wu, Q. T. Zhang, Z. H. Yuan, C. H. Wan, X. F. Han, T. Yu, K. Fukuda, H. Naganuma, and M.-J. Tung. Field-free spin Hall effect driven magnetization switching in Pd/Co/IrMn exchange coupling system. *Appl. Phys. Lett.*, 109:132402, 2016. URL <http://dx.doi.org/10.1063/1.4963235>.
- [80] B. Korenblum and E. I. Rashba. Classical Properties of Low-Dimensional Conductors: Giant Capacitance and Non-Ohmic Potential Drop. *Phys. Rev. Lett.*, 89:096803, 2002. URL <https://doi.org/10.1103/PhysRevLett.89.096803>.
- [81] T. Koyama, D. Chiba, K. Ueda, K. Kondou, H. Tanigawa, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, K. Kobayashi, and T. Ono. Observation of the intrinsic pinning of a magnetic domain wall in a ferromagnetic nanowire. *Nat. Mater.*, 10:194, 2011. URL <https://www.nature.com/articles/nmat2961>.
- [82] H. Kurebayashi, J. Sinova, D. Fang, A. C. Irvine, T. D. Skinner, J. Wunderlich, V. Novák, R. P. Campion, B. L. Gallagher, E. K. Vehstedt, L. P. Zârbo, K. Výborný, A. J. Ferguson, and T. Jungwirth. An antidamping spin-orbit torque originating from the Berry curvature. *Nat. Nanotechnol.*, 9:211–217, 2014. URL www.nature.com/doi/10.1038/nnano.2014.15.
- [83] A. Kurenkov, C. Zhang, S. DuttaGupta, S. Fukami, and H. Ohno. Device-size dependence of field-free spin-orbit torque induced magnetization switching in antiferromagnet/ferromagnet structures. *Appl. Phys. Lett.*, 110:092410, 2017. URL <http://dx.doi.org/10.1063/1.4977838>.
- [84] L. Landau and E. Lifshitz. On the Theory of the Dispersion of Magnetic Permeability in Ferromagnetic Bodies. *Phys. Z. Sowjet.*, 8:153, 1935.
- [85] Y.-C. Lau, D. Betto, K. Rode, J. M. D. Coey, and P. Stamenov. Spin-orbit torque switching without external field with a ferromagnetic exchange-biased coupling layer. *Nat. Nanotechnol.*, 11:758–762, 2016. URL <http://www.nature.com/nnano/journal/v11/n9/full/nnano.2016.84.html>.

- [86] K.-S. Lee, D. Go, A. Manchon, P. M. Haney, M. D. Stiles, H.-W. Lee, and K.-J. Lee. Angular dependence of spin-orbit spin-transfer torques. *Phys. Rev. B*, 91:144401, 2015. URL <https://doi.org/10.1103/PhysRevB.91.144401>.
- [87] S. Li, S. Goolaup, J. Kwon, F. Luo, W. Gan, and Wen Siang Lew. Deterministic Spin-Orbit Torque Induced Magnetization Reversal In Pt/[Co/Ni]_n/Co/Ta Multilayer Hall Bars. *Sci. Rep.*, 7:972, 2017. URL <https://www.nature.com/articles/s41598-017-01079-7>.
- [88] W. J. Lin, T. Y. Tseng, H. B. Lu, S. L. Tu, S. J. Yang, and I. N. Lin. Growth and ferroelectricity of epitaxial-like BaTiO₃ films on single-crystal MgO, SrTiO₃, and silicon substrates synthesized by pulsed laser deposition. *J. Appl. Phys.*, 77:6466, 1995. URL <http://dx.doi.org/10.1063/1.359121>.
- [89] K. Liu, K. Nagodawithana, P. C. Searson, and C. L. Chien. Perpendicular giant magnetoresistance of multilayered co/cu nanowires. *Phys. Rev. B*, 51:7381(R), 1995. URL <https://doi.org/10.1103/PhysRevB.51.7381>.
- [90] L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman. Reduction of the spin-torque critical current by partially canceling the free layer demagnetization field. *Appl. Phys. Lett.*, 94:122508, 2009. URL <http://dx.doi.org/10.1063/1.3107262>.
- [91] L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman. Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect. *Phys. Rev. Lett.*, 106:036601, 2011. URL <https://doi.org/10.1103/PhysRevLett.106.036601>.
- [92] L. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph, and R. A. Buhrman. Current-Induced Switching of Perpendicularly Magnetized Magnetic Layers Using Spin Torque from the Spin Hall Effect. *Phys. Rev. Lett.*, 109:096602, 2012. URL <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.109.096602>.
- [93] L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman. Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum. *Science*, 336:555–558, 2012. URL <http://science.sciencemag.org/content/336/6081/555>.
- [94] L. Liu, C.-F. Pai, D. C. Ralph, and R. A. Buhrman. Magnetic Oscillations Driven by the Spin Hall Effect in 3-Terminal Magnetic Tunnel Junction Devices. *Phys. Rev. Lett.*, 109:186602, 2012. URL <https://doi.org/10.1103/PhysRevLett.109.186602>.
- [95] R. Lo Conte, E. Martinez, A. Hrabec, A. Lamperti, T. Schulz, L. Nasi, L. Lazzarini, R. Mantovan, F. Maccherozzi, S. S. Dhesi,

- B. Ocker, C. H. Marrows, T. A. Moore, and M. Kläui. Role of B diffusion in the interfacial Dzyaloshinskii-Moriya interaction in Ta/Co₂₀Fe₆₀B₂₀/MgO nanowires. *Phys. Rev. B*, 91:014433, 2015. URL <https://doi.org/10.1103/PhysRevB.91.014433>.
- [96] F. Luo, S. Goolaup, W. C. Law, S. Li, F. Tan, C. Engel, T. Zhou, and W. S. Lew. Simultaneous determination of effective spin-orbit fields in magnetic structures with in-plane anisotropy. *Phys. Rev. B*, 95:174415, 2017. URL <https://doi.org/10.1103/PhysRevB.95.174415>.
- [97] A. Manchon and S. Zhang. Theory of nonequilibrium intrinsic spin torque in a single nanomagnet. *Phys. Rev. B*, 78:212405, 2008. URL <https://doi.org/10.1103/PhysRevB.78.212405>.
- [98] A. Manchon, H. C. Koo, J. Nitta, S. M. Frolov, and R. A. Duine. New perspectives for Rashba spin-orbit coupling. *Nat. Mater.*, 14: 871–882, 2015. URL <https://www.nature.com/nmat/journal/v14/n9/full/nmat4360.html>.
- [99] E. Martinez, S. Emori, N. Perez, L. Torres, and G. S. D. Beach. Current-driven dynamics of Dzyaloshinskii domain walls in the presence of in-plane fields: Full micromagnetic and one-dimensional analysis. *J. Appl. Phys.*, 115:213909, 2014. URL <http://aip.scitation.org/doi/abs/10.1063/1.4881778>.
- [100] T. R. McGuire and R. I. Potter. Anisotropic Magnetoresistance in Ferromagnetic 3d Alloys. *IEEE Trans. Magn.*, 11:1018–1038, 1975. URL <http://ieeexplore.ieee.org/abstract/document/1058782/>.
- [101] W. H. Meiklejohn and C. P. Bean. New Magnetic Anisotropy. *Phys. Rev.*, 102:1413, 1956. URL <https://doi.org/10.1103/PhysRev.102.1413>.
- [102] A. R. Mellnik, J. S. Lee, A. Richardella, J. L. Grab, P. J. Mintun, M. H. Fischer, A. Vaezi, A. Manchon, E.-A. Kim, N. Samarth, and D. C. Ralph. Spin-transfer torque generated by a topological insulator. *Nature*, 511:449, 2014. URL <https://www.nature.com/nature/journal/v511/n7510/full/nature13534.html>.
- [103] K. K. Meng, J. Miao, X. G. Xu, J. X. Xiao, J. H. Zhao, and Y. Jiang. Anomalous Hall effect in Mn_{1.5}Ga/Ta and Mn_{1.5}Ga/Pt bilayers: Modification from spin-orbit coupling of heavy metals. *Phys. Rev. B*, 93:060406(R), 2016. URL <https://journals.aps.org/prb/abstract/10.1103/PhysRevB.93.060406>.
- [104] I. M. Miron, G. Gaudin, S. Auffret, B. Rodmacq, A. Schuhl, S. Pizzini, J. Vogel, and P. Gambardella. Current-driven spin torque induced by the rashba effect in a ferromagnetic metal

- layer. *Nat. Mater.*, 9:230–234, 2010. URL <https://www.nature.com/nmat/journal/v9/n3/abs/nmat2613.html>.
- [105] I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella. Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. *Nature*, 476:189–193, 2011. URL <http://www.nature.com/nature/journal/v476/n7359/full/nature10309.html>.
- [106] T. Miyazaki and N. Tezuka. Giant magnetic tunneling effect in Fe/Al₂O₃/Fe junction. *J. Magn. Magn. Mater.*, 139:L231–L234, 1995. URL [https://doi.org/10.1016/0304-8853\(95\)90001-2](https://doi.org/10.1016/0304-8853(95)90001-2).
- [107] M. Montazeri, P. Upadhyaya, M. C. Onbasli, G. Yu, K. L. Wong, M. Lang, Y. Fan, X. Li, P. K. Amiri, R. N. Schwartz, C. A. Ross, and K. L. Wang. Magneto-optical investigation of spin-orbit torques in metallic and insulating magnetic heterostructures. *Nat. Commun.*, 6:8958, 2015. URL <https://www.nature.com/articles/ncomms9958>.
- [108] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey. Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions. *Phys. Rev. Lett.*, 74:3273, 1995. URL <https://doi.org/10.1103/PhysRevLett.74.3273>.
- [109] N. F. Mott. The scattering of fast electrons by atomic nuclei. *Proceedings of the Royal society A*, 124:425–441, 1929. URL <http://rspa.royalsocietypublishing.org/content/124/794/425>.
- [110] S. Murakami, N. Nagaosa, and S.-C. Zhang. Dissipationless Quantum Spin Current at Room Temperature. *Science*, 301:1348–1351, 2003. URL <http://science.sciencemag.org/content/301/5638/1348>.
- [111] N. Nakajima, T. Koide, T. Shidara, H. Miyauchi, H. Fukutani, A. Fujimori, K. Iio, T. Katayama, M. Nývlt, and Y. Suzuki. Perpendicular Magnetic Anisotropy Caused by Interfacial Hybridization via Enhanced Orbital Moment in Co/Pt Magnetic Circular X-Ray Dichroism Study. *Phys. Rev. Lett.*, 81:5229–5232, 1998. URL <https://doi.org/10.1103/PhysRevLett.81.5229>.
- [112] H. Nakayama, M. Althammer, Y.-T. Chen, K. Uchida, Y. Kajiwara, D. Kikuchi, T. Ohtani, S. Geprägs, M. Opel, S. Takahashi, R. Gross, G. E. W. Bauer, S. T. B. Goennenwein, and E. Saitoh. Spin Hall Magnetoresistance Induced by a Nonequilibrium Proximity Effect. *Phys. Rev. Lett.*, 110:206601, 2013. URL <https://doi.org/10.1103/PhysRevLett.110.206601>.

- [113] D. Navas, J. Torrejon, F. Béron, C. Redondo, F. Batallan, B. P. Toperverg, A. Devishvili, B. Sierra, F. Castaño, K. R. Pirota, and C. A. Ross. Magnetization reversal and exchange bias effects in hard/soft ferromagnetic bilayers with orthogonal anisotropies. *New J. Phys.*, 14:113001, 2012. URL <http://iopscience.iop.org/article/10.1088/1367-2630/14/11/113001/meta>.
- [114] A. J. Newell, W. Williams, and D. J. Dunlop. A generalization of the demagnetization tensor for nonuniform magnetization. *J. Geophysical Research*, 98:9551–9555, 1993. URL <http://onlinelibrary.wiley.com/doi/10.1029/93JB00694/full>.
- [115] G. Niu, S. Yin, G. Saint-Girons, B. Gautier, P. Lecoeur, V. Pillard, G. Hollinger, and B. Vilquin. Epitaxy of BaTiO₃ thin film on Si (001) using a SrTiO₃ buffer layer for non-volatile memory application. *Microelectron. Eng.*, 88:1232–1235, 2011. URL <https://doi.org/10.1016/j.mee.2011.03.028>.
- [116] J. Nogués and I. K. Schuller. Exchange bias. *J. Magn. Magn. Mater.*, 192:203–232, 1999. URL [https://doi.org/10.1016/S0304-8853\(98\)00266-2](https://doi.org/10.1016/S0304-8853(98)00266-2).
- [117] K. Obata and G. Tatara. Current-induced domain wall motion in Rashba spin-orbit system. *Phys. Rev. B*, 77:214429, 2008. URL <https://doi.org/10.1103/PhysRevB.77.214429>.
- [118] S. C. Oh, J. E. Lee, H.-J. Kim, Y. K. Ha, J. S. Bae, K. T. Nam, E. S. Kim, S. O. Park, H. S. Kim, U.-I. Chung, and J. T. Moon. Improvement of writing margin in mram with novel shape. *J. Appl. Phys.*, 97:10P509, 2005. URL <http://dx.doi.org/10.1063/1.1861433>.
- [119] S. Ok, W. Chen, M. Sigrist, and D. Manske. Effect of quantum tunneling on spin Hall magnetoresistance. *J. Phys. Condens. Matter*, 29:075802, 2016. URL <http://stacks.iop.org/0953-8984/29/i=7/a=075802>.
- [120] K. Okamoto. A new method for analysis of magnetic anisotropy in films using the spontaneous hall effect. *J. Magn. Magn. Mater.*, 35:353–355, 1983. URL [https://doi.org/10.1016/0304-8853\(83\)90539-5](https://doi.org/10.1016/0304-8853(83)90539-5).
- [121] C. Ortiz Pauyac, X. Wang, M. Chshiev, and A. Manchon. Angular dependence and symmetry of Rashba spin torque in ferromagnetic heterostructures. *Appl. Phys. Lett.*, 102:252403, 2013. URL <http://dx.doi.org/10.1063/1.4812663>.
- [122] J. A. Osborn. Demagnetizing Factors of the General Ellipsoid. *Phys. Rev.*, 67:351, 1945. URL <https://doi.org/10.1103/PhysRev.67.351>.

- [123] Y. Ou, C.-F. Pai, S. Shi, D. C. Ralph, and R. A. Buhrman. Origin of fieldlike spin-orbit torques in heavy metal/ferromagnet/oxide thin film heterostructures. *Phys. Rev. B.*, 94:140414(R), 2016. URL <https://www.nature.com/articles/ncomms9958>.
- [124] C.-F. Pai, L. Liu, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. *Appl. Phys. Lett.*, 101:240–245, 2012. URL <http://aip.scitation.org/doi/abs/10.1063/1.4753947>.
- [125] C.-F. Pai, M. Mann, A. J. Tan, and S. D. Beach. Determination of spin torque efficiencies in heterostructures with perpendicular magnetic anisotropy. *Phys. Rev. B*, 93:144409, 2016. URL <https://doi.org/10.1103/PhysRevB.93.144409>.
- [126] M. Pakala, Y. Huai, G. Anderson, and L. Miloslavsky. Effect of underlayer roughness, grain size, and crystal texture on the exchange coupled IrMn/CoFe thin films. *J. Appl. Phys.*, 87:6653–6655, 2000. URL <http://dx.doi.org/10.1063/1.372800>.
- [127] J. P. Pan. *Solid State Physics*. Academic, New York, 1957.
- [128] S. S. P. Parkin, C. Kaiser, A. Panchula, P. M. Rice, B. Hughes, M. Samant, and S.-H. Yang. Giant tunneling magnetoresistance at room temperature with MgO (100) tunnel barriers. *Nat. Mater.*, 3:862–867, 2004. URL <https://www.nature.com/nmat/journal/v3/n12/abs/nmat1256.html>.
- [129] D. A. Pesin and A. H. MacDonald. Quantum kinetic theory of current-induced torques in Rashba ferromagnets. *Phys. Rev. B*, 86:014416, 2012. URL <https://doi.org/10.1103/PhysRevB.86.014416>.
- [130] U. H. Pi, K. W. Kim, J. Y. Bae, S. C. Lee, Y. J. Cho, K. S. Kim, and S. Seo. Tilting of the spin orientation induced by Rashba effect in ferromagnetic metal layer. *Appl. Phys. Lett.*, 97:162507, 2010. URL <http://aip.scitation.org/doi/abs/10.1063/1.3502596>.
- [131] X. Qiu, P. Deorani, K. Narayanapillai, K.-S. Lee, K.-J. Lee, H.-W. Lee, and H. Yang. Angular and temperature dependence of current induced spin-orbit effective fields in Ta/CoFeB/MgO nanowires. *Sci. Rep.*, 4:4491, 2014. URL <https://www.nature.com/articles/srep04491>.
- [132] D. Ravelosona, D. Lacour, J. A. Katine, B. D. Terris, and C. Chappert. Nanometer Scale Observation of High Efficiency Thermally Assisted Current-Driven Domain Wall Depinning. *Phys. Rev. Lett.*, 95:117203, 2005. URL <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.95.117203>.

- [133] S. A. Razavi, D. Wu, G. Yu, Y.-C. Lau, K. L. Wong, W. Zhu, W. He, Z. Zhang, J. M. D. Coey, P. Stamenov, P. K. Amiri, and K. L. Wang. Joule Heating Effect on Field-Free Magnetization Switching by Spin-Orbit Torque in Exchange-Biased Systems. *Phys. Rev. Appl.*, 7:024023, 2017. URL <https://doi.org/10.1103/PhysRevApplied.7.024023>.
- [134] S. M. Rezende, F. M. de Aguiar, and A. Azevedo. Spin-Wave Theory for Dynamics Induced by Direct Currents in Magnetic Multilayers. *Phys. Rev. Lett.*, 94:037202, 2005. URL <https://doi.org/10.1103/PhysRevLett.94.037202>.
- [135] K.-S. Ryu, L. Thomas, S.-H. Yang, and S. Parkin. Chiral spin torque at magnetic domain walls. *Nat. Nanotechnol.*, 8:527–533, 2013. URL <https://www.nature.com/nnano/journal/v8/n7/abs/nnano.2013.102.html>.
- [136] K. Sakanashi, M. Sigrist, and W. Chen. Theory of in-plane current induced spin torque in metal/ferromagnet bilayers. *arXiv*, preprint:arXiv:1707.02771, 2017. URL <https://arxiv.org/abs/1707.02771>.
- [137] T. Schulz, O. Alejos, E. Martinez, K. M. D. Hals, K. Garcia, L. Vila, K. Lee, R. Lo Conte, G. V. Karnad, S. Moretti, B. Ocker, D. Ravelosona, A. Brataas, and M. Kläui. Spin-orbit torques for current parallel and perpendicular to a domain wall. *Appl. Phys. Lett.*, 107:122405, 2015. URL <http://dx.doi.org/10.1063/1.4931429>.
- [138] P. Sethi, S. Krishnia, W. L. Gan, F. N. Kholid, F. N. Tan, R. Maddu, and W. S. Lew. Bi-directional high speed domain wall motion in perpendicular magnetic anisotropy Co/Pt double stack structures. *Sci. Rep.*, 7:4964, 2017. URL <https://www.nature.com/articles/s41598-017-05409-7>.
- [139] P. Sethi, S. Krishnia, S. H. Li, and W. S. Lew. Modulation of spin-orbit torque efficiency by thickness control of heavy metal layers in Co/Pt multilayers. *J. Magn. Magn. Mater.*, 426:497–503, 2017. URL <https://www.sciencedirect.com/science/article/abs/pii/S0304885316324283>.
- [140] J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, and A. H. MacDonald. Universal Intrinsic Spin Hall Effect. *Phys. Rev. Lett.*, 92:126603, 2004. URL <https://doi.org/10.1103/PhysRevLett.92.126603>.
- [141] R. Skomski. *Simple Models of Magnetism*. Oxford University Press Inc., New York, 2008.

- [142] J. C. Slonczewski. Current-driven excitation of magnetic multilayers. *J. Magn. Magn. Mater.*, 159:L1–L7, 1996. URL [https://doi.org/10.1016/0304-8853\(96\)00062-5](https://doi.org/10.1016/0304-8853(96)00062-5).
- [143] J. Smit. The spontaneous hall effect in ferromagnetics I. *Physica*, 21:877–887, 1955. URL [https://doi.org/10.1016/S0031-8914\(55\)92596-9](https://doi.org/10.1016/S0031-8914(55)92596-9).
- [144] J. Smit. The spontaneous hall effect in ferromagnetics II. *Physica*, 24:39–51, 1958. URL [https://doi.org/10.1016/S0031-8914\(58\)93541-9](https://doi.org/10.1016/S0031-8914(58)93541-9).
- [145] M. D. Stiles and R. D. McMichael. Model for exchange bias in polycrystalline ferromagnet-antiferromagnet bilayers. *Phys. Rev. B*, 59:3722–3733, 1999. URL <https://doi.org/10.1103/PhysRevB.59.3722>.
- [146] E. C. Stoner and E. P. Wohlfart. *A mechanism of magnetic hysteresis in heterogeneous alloys*. Philos. Trans. Roy. Soc., London, 1948.
- [147] J. Z. Sun. Spin-current interaction with a monodomain magnetic body: A model study. *Phys. Rev. B*, 62:570–578, 2000. URL <https://doi.org/10.1103/PhysRevB.62.570>.
- [148] D. D. Tang and Y.-J. Lee. *Magnetic Memory: Fundamentals and Technology*. Cambridge University Press, Cambridge, 2010.
- [149] H. Tanigawa, T. Koyama, G. Yamada, D. Chiba, S. Kasai, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, and T. Ono. Domain Wall Motion Induced by Electric Current in a Perpendicular Magnetized Co/Ni Nano-Wire. *Appl. Phys. Express*, 2:053002, 2009. URL <http://iopscience.iop.org/article/10.1143/APEX.2.053002/meta>.
- [150] A. Thiaville, Y. Nakatani, J. Miltat, and N. Vernier. Domain wall motion by spin-polarized current: a micromagnetic study. *J. Appl. Phys.*, 95:7049, 2004. URL <http://dx.doi.org/10.1063/1.1667804>.
- [151] A. Thiaville, Y. Nakatani, J. Miltat, and Y. Suzuki. Micro-magnetic understanding of current-driven domain wall motion in patterned nanowires. *Europhys. Lett.*, 69:990–996, 2005. URL <http://iopscience.iop.org/article/10.1209/epl/i2004-10452-6/meta>.
- [152] A. Thiaville, S. Rohart, E. Jué, V. Cros, and A. Fert. Dynamics of Dzyaloshinskii domain walls in ultrathin magnetic films. *Europhys. Lett.*, 100:57002, 2012. URL <http://iopscience.iop.org/article/10.1209/0295-5075/100/57002/meta>.

- [153] J. Torrejon, J. Kim, J. Sinha, S. Mitani, M. Hayashi, M. Yamanouchi, and H. Ohno. Interface control of the magnetic chirality in coFeB/mgO heterostructures with heavy-metal underlayers. *Nat. Commun.*, 5:4655, 2014. URL <https://www.nature.com/articles/ncomms5655>.
- [154] C. H. Tsang, R. E. Fontana, T. Lin, D. E. Heim, B. A. Gurney, and M. L. Williams. Design, fabrication, and performance of spin-valve read heads for magnetic recording applications. *IBM J. Res. Dev.*, 42:103–116, 1998. URL <http://ieeexplore.ieee.org/abstract/document/5389313/>.
- [155] K. Ueda, T. Koyama, D. Chiba, K. Shimamura, H. Tanigawa, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, and T. Ono. Current-Induced Magnetic Domain Wall Motion in Co/Ni Nanowire at Low Temperature. *Appl. Phys. Express*, 4:063003, 2011. URL <http://iopscience.iop.org/article/10.1143/APEX.4.063003/meta>.
- [156] B. Újfalussy, L. Szunyogh, P. Bruno, and P. Weinberger. First-Principles Calculation of the Anomalous Perpendicular Anisotropy in a Co Monolayer on Au(111). *Phys. Rev. Lett.*, 77:1805–1808, 1996. URL <https://doi.org/10.1103/PhysRevLett.77.1805>.
- [157] A. van den Brink, G. Vermijs, A. Solignac, J. Koo, J. T. Kohlhepp, H. J. M. Swagten, and B. Koopmans. Field-free magnetization reversal by spin-Hall effect and exchange bias. *Nat. Commun.*, 7:10854, 2016. URL <https://www.nature.com/articles/ncomms10854>.
- [158] S. Veléz, N. Golovach, A. Bedoya-Pinto, M. Isasa, E. Sagasta, M. Abadia, C. Rogero, L. E. Hueso, F. S. Bergeret, and F. Casanova. Hanle Magnetoresistance in Thin Metal Films with Strong Spin-Orbit Coupling. *Phys. Rev. Lett.*, 116:016603, 2016. URL <https://doi.org/10.1103/PhysRevLett.116.016603>.
- [159] N. Vlietstra, J. Shan, V. Castel, B. J. van Wees, and J. Ben Youssef. Spin-Hall magnetoresistance in platinum on yttrium iron garnet: Dependence on platinum thickness and in-plane/out-of-plane magnetization. *Phys. Rev. B*, 87:184421, 2013. URL <https://doi.org/10.1103/PhysRevB.87.184421>.
- [160] I. Žutić, J. Fabian, and S. Das Sarma. Spintronics: Fundamentals and applications. *Rev. Mod. Phys.*, 76:323–410, 2004. URL <https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.76.323>.
- [161] K. L. Wang, J. G. Alzate, and P. Khalili Amiri. Low-power non-volatile spintronic memory: Stt-ram and beyond. *J. Phys. D:*

- Appl. Phys.*, 46:074003, 2013. URL <http://iopscience.iop.org/article/10.1088/0022-3727/46/7/074003/meta>.
- [162] X. Wang and A. Manchon. Diffusive Spin Dynamics Ferromagnetic Thin Films with a Rashba Interaction. *Phys. Rev. Lett.*, 108:117201, 2012. URL <https://doi.org/10.1103/PhysRevLett.108.117201>.
- [163] M. Weiler, M. Althammer, F. D. Czeschka, H. Huebl, M. S. Wagner, M. Opel, I.-M. Imort, G. Reiss, A. Thomas, R. Gross, and S. T. B. Goennenwein. Local Charge and Spin Currents in Magnetothermal Landscapes. *Phys. Rev. Lett.*, 108:106602, 2012. URL <https://doi.org/10.1103/PhysRevLett.108.106602>.
- [164] D. Weller, Y. Wu, J. Stöhr, M. G. Samant, B. D. Hermsmeier, and C. Chappert. Orbital magnetic moments of Co in multilayers with perpendicular magnetic anisotropy. *Phys. Rev. B*, 49:12888–12896, 1994. URL <https://doi.org/10.1103/PhysRevB.49.12888>.
- [165] A. W. J. Wells, P. M. Shepley, C. H. Marrows, and T. A. Moore. Effect of interfacial intermixing on the Dzyaloshinskii-Moriya interaction in Pt/Co/Pt. *Phys. Rev. B*, 95:054428, 2017. URL <https://doi.org/10.1103/PhysRevB.95.054428>.
- [166] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger. Spintronics: A Spin-Based Electronics Vision for the Future. *Science*, 294:1488–1495, 2001. URL <http://science.sciencemag.org/content/294/5546/1488.full>.
- [167] S. Woo, M. Mann, A. J. Tan, L. Caretta, and S. D. Beach. Enhanced spin-orbit torques in Pt/Co/Ta heterostructures. *Appl. Phys. Lett.*, 105:212404, 2014. URL <http://aip.scitation.org/doi/abs/10.1063/1.4902529>.
- [168] J. Wunderlich, B. Kaestner, J. Sinova, and T. Jungwirth. Experimental Observation of the Spin-Hall Effect in a Two-Dimensional Spin-Orbit Coupled Semiconductor System. *Phys. Rev. Lett.*, 94:047204, 2005. URL <https://doi.org/10.1103/PhysRevLett.94.047204>.
- [169] W. Xu. Screening length and quantum and transport mobilities of a heterojunction in the presence of the Rashba effect. *Phys. Rev. B*, 71:245304, 2005. URL <https://doi.org/10.1103/PhysRevB.71.245304>.
- [170] R. Yanes, J. Jackson, L. Udvardi, L. Szunyogh, and U. Nowak. Exchange Bias Driven by Dzyaloshinskii-Moriya Interactions. *Phys. Rev. Lett.*, 111:217202, 2013. URL <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.111.217202>.

- [171] C.-Y. You. Simulations for Spin Transfer Torque in Magnetic Multilayers. *J. Magn.*, 17:73–77, 2012. URL <https://doi.org/10.4283/JMAG.2012.17.2.073>.
- [172] C.-Y. You and H. Kim. Metastable Vortex State of Perpendicular Magnetic Anisotropy Free Layer in Spin Transfer Torque Magnetic Tunneling Junctions. *J. Magn.*, 18:380–385, 2013. URL <http://dx.doi.org/10.4283/JMAG.2013.18.4.380>.
- [173] C.-Y. You, J. Yoon, S.-Y. Park, S. Yuasa, and M.-H. Jung. Magnetic noise spectra and spin transfer torque of a magnetic tunnel junction with an exchange biased synthetic ferromagnetic reference layer. *Curr. Appl. Phys.*, 11:e92–e94, 2011. URL <https://doi.org/10.1016/j.cap.2010.11.128>.
- [174] G. Yu, P. Upadhyaya, Y. Fan, J. G. Alzate, W. Jiang, K. L. Wong, S. Takei, S. A. Bender, L.-T. Chang, Y. Jiang, M. Lang, J. Tang, Y. Wang, Y. Tservnyak, P. K. Amiri, and K. L. Wang. Switching of perpendicular magnetization by spin-orbit torques in the absence of external magnetic fields. *Nat. Nanotechnol.*, 9:548–554, 2014. URL <http://www.nature.com/nnano/journal/v9/n7/full/nnano.2014.94.html>.
- [175] J. Yu, X. Qiu, Y. Wu, J. Yoon, P. Deorani, J. M. Besbach, A. Manchon, and H. Yang. Spin orbit torques and Dzyaloshinskii-Moriya interaction in dual-interfaced Co-Ni multilayers. *Sci. Rep.*, 6:32629, 2016. URL <https://www.nature.com/articles/srep32629>.
- [176] S. Zhang. Spin Hall Effect in the Presence of Spin Diffusion. *Phys. Rev. Lett.*, 85:393–396, 2000. URL <https://doi.org/10.1103/PhysRevLett.85.393>.
- [177] S. Zhang and Z. Li. Roles of Nonequilibrium Conduction Electrons on the Magnetization Dynamics of Ferromagnets. *Phys. Rev. Lett.*, 93:127204, 2004. URL <https://doi.org/10.1103/PhysRevLett.93.127204>.
- [178] S. Zhang, P. M. Levy, and A. Fert. Mechanisms of Spin-Polarized Current-Driven Magnetization Switching. *Phys. Rev. Lett.*, 88:236601, 2002. URL <https://doi.org/10.1103/PhysRevLett.88.236601>.
- [179] S. S.-L. Zhang, G. Vignale, and S. Zhang. Anisotropic magnetoresistance driven by surface spin-orbit scattering. *Phys. Rev. B*, 92:024412, 2015. URL <https://doi.org/10.1103/PhysRevB.92.024412>.
- [180] T. Zhang and M. Dressel. Grain-size effects on the charge ordering and exchange bias in $\text{Pr}_{0.5}\text{Ca}_{0.5}\text{MnO}_3$: The role of

spin configuration. *Phys. Rev. B*, 80:014435, 2009. URL <https://doi.org/10.1103/PhysRevB.80.014435>.

LIST OF PUBLICATIONS

1. C. Engel, S. Goolaup, F. Luo, W. S. Lew, Quantitative characterization of spin-orbit torques in Pt/Co/Pt/Co/ Ta/BTO heterostructures due to the magnetization azimuthal angle dependence, *Physical Review B*, **96**, 054407 (2017) <https://doi.org/10.1103/PhysRevB.96.054407>.
2. C. Engel, S. Goolaup, H. K. Teoh, W. S. Lew, Effect of geometrical modulation on pMTJ magnetization reversal, *IEEE Transactions on Magnetics*, **53**, 7100707 (2017) <https://ieeexplore.ieee.org/abstract/document/8002645/>.
3. C. Engel, S. Goolaup, F. Luo, W. S. Lew, Characterizing angular dependence of spin-orbit torque effective fields in Pt/(Co/Ni)₂/Co/IrMn structure, *IEEE Transactions on Magnetics*, **53**, 1400604 (2017) <https://ieeexplore.ieee.org/document/7929382/>.
4. C. Engel, S. Goolaup, F. Luo, W. Gan, W. S. Lew, Spin-orbit torque induced magnetization anisotropy modulation in Pt/(Co/Ni)₄/Co/IrMn heterostructure, *Journal of Applied Physics*, **121**, 143902 (2017) <http://dx.doi.org/10.1063/1.4980108>.
5. F. Luo, S. Goolaup, W. C. Law, S. Li, F. Tan, C. Engel, T. Zhou, W. S. Lew, Simultaneous determination of effective spin-orbit fields in magnetic structures with in-plane anisotropy, *Physical Review B*, **95**, 174415 (2017) <https://doi.org/10.1103/PhysRevB.95.174415>.
6. F. Luo, S. Goolaup, S. Li, G. J. Lim, F. Tan, C. Engel, S. Zhang, F. Ma, T. Zhou, W. S. Lew, Characterizing the spin orbit torque field-like term in in-plane magnetic system using transverse field, *Journal of Applied Physics*, **120**, 083908 (2016) <https://doi.org/10.1063/1.4961952>.
7. F. Luo, S. Goolaup, C. Engel, W. S. Lew, Quantification of spin accumulation causing spin-orbit torque in Pt/Co/Ta stack, e-print [arXiv:1709.07948](https://arxiv.org/abs/1709.07948) (2017).