harmonic measurement of NiPS3

outline

- why harmonic measurement
- theoretical work review
- others data
- guess for NiPS3

Why harmonic measurement

$$R(I) = R(0) + \frac{\partial R}{\partial I} I + \frac{1}{2} \frac{\partial^2 R}{\partial I^2} I^2$$

plug in $I = I_0 \cos \omega t$ into $V = IR$

$$\begin{aligned} V &= IR \\ &= R(0) I_0 \cos \omega t + \frac{\partial R}{\partial I} I_0^2 \cos^2 \omega t^2 + \frac{1}{2} \frac{\partial^2 R}{\partial I^2} I_0^3 \cos^3 \omega t + \cdots \\ &\approx R(0) I_0 \cos \omega t + \frac{1}{2} \frac{\partial R}{\partial I} I_0^2 \cos 2\omega t + \frac{1}{8} \frac{\partial^2 R}{\partial I^2} I_0^3 \cos 3\omega t + \cdots \end{aligned}$$

$$V_{2\omega} = \frac{1}{2} \frac{\partial R}{\partial I} I_0^2$$

$$V_{3\omega} = \frac{1}{8} \frac{\partial^2 R}{\partial I^2} I_0^3$$

theoretical review

PHYSICAL REVIEW B **87**, 144411 (2013)

Theory of spin Hall magnetoresistance

Yan-Ting Chen,[1] Saburo Takahashi,[2] Hiroyasu Nakayama,[2] Matthias Althammer,[3,4] Sebastian T. B. Goennenwein,[3]
Eiji Saitoh,[2,5,6,7] and Gerrit E. W. Bauer[1,2,5]
[1]*Kavli Institute of NanoScience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
[2]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[3]*Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*
[4]*Center for Materials for Information Technology MINT, Department of Chemistry, University of Alabama, Tuscaloosa, Alabama 35487, USA*
[5]*WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[6]*CREST, Japan Science and Technology Agency, Tokyo 102-0076, Japan*
[7]*The Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
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We present a theory of the spin Hall magnetoresistance (SMR) in multilayers made from an insulating ferromagnet F, such as yttrium iron garnet (YIG), and a normal metal N with spin-orbit interactions, such as platinum (Pt). The SMR is induced by the simultaneous action of spin Hall and inverse spin Hall effects and therefore a nonequilibrium proximity phenomenon. We compute the SMR in F|N and F|N|F layered systems, treating N by spin-diffusion theory with quantum mechanical boundary conditions at the interfaces in terms of the spin-mixing conductance. Our results explain the experimentally observed spin Hall magnetoresistance in N|F bilayers. For F|N|F spin valves we predict an enhanced SMR amplitude when magnetizations are collinear. The SMR and the spin-transfer torques in these trilayers can be controlled by the magnetic configuration.

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$$\rho_{\mathrm{long}} = \sigma_{\mathrm{long}}^{-1} = \left(\frac{\overline{j_{c,\mathrm{long}}}}{E_x} \right)^{-1} \approx \rho + \Delta\rho_0 + \Delta\rho_1 \left(1 - m_y^2\right), \tag{19}$$

$$\rho_{\mathrm{trans}} = -\frac{\sigma_{\mathrm{trans}}}{\sigma_{\mathrm{long}}^2} \approx -\frac{\overline{j_{c,\mathrm{trans}}}/E_x}{\sigma^2} = \Delta\rho_1 m_x m_y + \Delta\rho_2 m_z, \tag{20}$$

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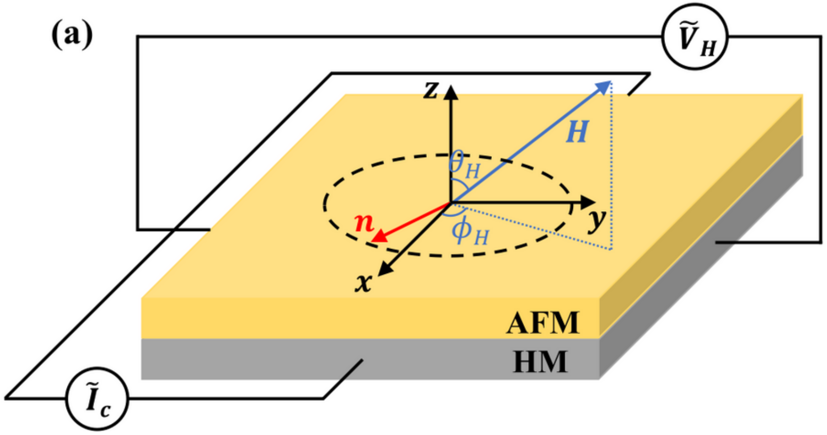

Research article

Theory of harmonic Hall responses of spin-torque driven antiferromagnets

Hantao Zhang [a], Ran Cheng [a,b,*]

[a] Department of Electrical and Computer Engineering, University of California, 900 University Avenue, Riverside, 92521, CA, United States
[b] Department of Physics and Astronomy, University of California, 900 University Avenue, Riverside, 92521, CA, United States

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ABSTRACT

Harmonic analysis is a powerful tool to characterize and quantify current-induced torques acting on magnetic materials, but so far it remains an open question in studying antiferromagnets. Here we formulate a general theory of harmonic Hall responses of collinear antiferromagnets driven by current-induced torques including both field-like and damping-like components. By scanning a magnetic field of variable strength in three orthogonal planes, we are able to distinguish the contributions from field-like torque, damping-like torque, and concomitant thermal effects by analyzing the second harmonic signals in the Hall voltage. The analytical expressions of the first and second harmonics as functions of the magnetic field direction and strength are confirmed by numerical simulations with good agreement. We demonstrate our predictions in two prototype antiferromagnets, α–Fe_2O_3 and NiO, providing direct and general guidance to current and future experiments.

$$R_H = R_0 n_x n_y$$

$$n_x = \sin\phi_H + \Delta\phi\cos\phi_H,$$

$$n_y = -\cos\phi_H + \Delta\phi\sin\phi_H$$

$$n_z = -\Delta\theta_H,$$

$$V_{1\omega} = -\frac{1}{2} I_0 R_0 \sin(2\phi_H),$$

$$V_{2\omega} = -\frac{1}{2} I_0 R_0 \Bigg[\frac{H_F \cos(2\phi_H)\cos\phi_H}{H\sin\theta_H} - \frac{H_D H_E H \cos\theta_H \cos(2\phi_H)\sin\phi_H}{(D^2 + 2H_E H_\perp) H \sin\theta_H + D(H^2 + 4H_E H_\perp + D^2)/2} \Bigg]$$

$$\frac{E}{\hbar\gamma} = H_E \boldsymbol{S}_1 \cdot \boldsymbol{S}_2 + H_\perp \sum_{i=1}^{2} (\boldsymbol{S}_i \cdot \hat{\boldsymbol{z}})^2 - H_\parallel \sum_{i=1}^{2} (\boldsymbol{S}_i \cdot \hat{\boldsymbol{x}})^2 - D\hat{\boldsymbol{z}} \cdot (\boldsymbol{S}_1 \times \boldsymbol{S}_2) - \boldsymbol{H}_t \cdot (\boldsymbol{S}_1 + \boldsymbol{S}_2),$$

The AFM dynamics can be described by the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation

$$\frac{d\boldsymbol{S}_i}{\gamma dt} = \boldsymbol{H}_{\mathrm{eff},i} \times \boldsymbol{S}_i + (\boldsymbol{H}_D \times \boldsymbol{S}_i) \times \boldsymbol{S}_i, \qquad \boldsymbol{H}_{\mathrm{eff},i} = -(1/\hbar\gamma)\delta E/\delta \boldsymbol{S}_i$$

$$\boldsymbol{n} \times \left\{ \frac{1}{2H_E} \left[-\frac{\partial^2 \boldsymbol{n}}{\partial t^2} - \frac{\partial \boldsymbol{n}}{\partial t} \times \boldsymbol{H}_t + \frac{\partial}{\partial t} \left(\boldsymbol{H}_t \times \boldsymbol{n} \right) - D\hat{\boldsymbol{z}}(D\hat{\boldsymbol{z}} \cdot \boldsymbol{n}) - D\hat{\boldsymbol{z}} \times \boldsymbol{H}_t - (\boldsymbol{n} \cdot \boldsymbol{H}_t)\boldsymbol{H}_t \right] - 2H_\perp(\boldsymbol{n} \cdot \hat{\boldsymbol{z}})\hat{\boldsymbol{z}} + 2H_\parallel(\boldsymbol{n} \cdot \hat{\boldsymbol{x}})\hat{\boldsymbol{x}} \right\} = \boldsymbol{n} \times (\boldsymbol{n} \times \boldsymbol{H}_D).$$

E.O.M of Neel vector

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Magnetic anisotropy and exchange interactions of two-dimensional $FePS_3$, $NiPS_3$ and $MnPS_3$ from first principles calculations

Thomas Olsen

Computational Atomic-Scale Materials Design (CAMD), Department of Physics, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

E-mail: tolsen@fysik.dtu.dk

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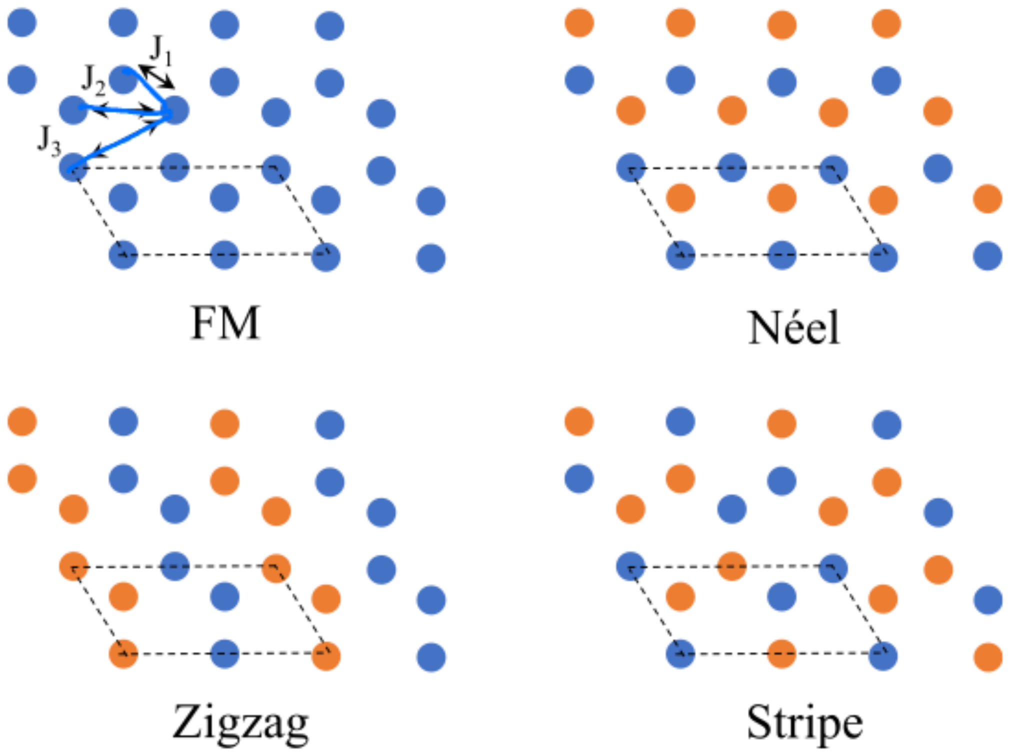
Abstract

The van der Waals bonded transition metal phosphorous trichalcogenides $FePS_3$, $NiPS_3$ and $MnPS_3$ have recently attracted renewed attention due to the possibility of exfoliating them into their monolayers. Although the three compounds have similar electronic structure, the magnetic structure differs due to subtle differences in exchange and magnetic anisotropy and the materials thus comprise a unique playground for studying different aspects of magnetism in 2D. Here we calculate the exchange and anisotropy parameters of the three materials from first principles paying special attention to the choice of Hubbard parameter U. We find a strong dependence of the choice of U and show that the calculated Néel temperature of $FePS_3$ varies by an order of magnitude over commonly applied values of U for the Fe d-orbitals. The results are compared with parameters fitted to experimental spin-wave spectra of the bulk materials and we find excellent agreement between the exchange constants when a proper value of U is chosen. However, the anisotropy parameters are severely underestimated by density functional theory and we discuss possible origins of this discrepancy.

Keywords: magnetism, anti-ferromagnetism, 2D materials, first principles, density functional theory, magnetic order in 2D

(Some figures may appear in colour only in the online journal)



Material	J_1	J_2	J_3	λ_1	λ_3	λ_3	A
$FePS_3$ ($U = 2$ eV)	2.1	−0.21	−2.6	-4.1×10^{-3}	1.1×10^{-3}	2.5×10^{-3}	0.101
$FePS_3$ (experimental) [15]	2.92	−0.08	−1.92	—	—	—	2.66
$NiPS_3$ ($U = 3$ eV)	2.6	0.32	−14	-0.32×10^{-3}	-0.51×10^{-3}	-0.25×10^{-3}	−0.018
$NiPS_3$ (experimental) [16]	3.8	−0.2	−13.8	—	—	—	0.3
$MnPS_3$ ($U = 3$ eV)	−1.42	−0.081	−0.52	-1.2×10^{-3}	-0.19×10^{-3}	0.37×10^{-3}	−0.0035
$MnPS_3$ (experimental) [13]	−1.54	−0.14	−0.36	—	—	—	0.0086

others data

key word:

antiferromagnetic, second harmonic, Hall effect

Quantifying Spin-Orbit Torques in Antiferromagnet–Heavy-Metal Heterostructures

Egecan Cogulu,[1] Hantao Zhang,[2] Nahuel N. Statuto,[1] Yang Cheng,[3] Fengyuan Yang,[3] Ran Cheng,[2,4] and Andrew D. Kent[1]

[1]*Center for Quantum Phenomena, Department of Physics, New York University, New York 10003, USA*
[2]*Department of Electrical and Computer Engineering, University of California, Riverside, California 92521, USA*
[3]*Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*
[4]*Department of Physics and Astronomy, University of California, Riverside, California 92521, USA*

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The effect of spin currents on the magnetic order of insulating antiferromagnets (AFMs) is of fundamental interest and can enable new applications. Toward this goal, characterizing the spin-orbit torques (SOTs) associated with AFM–heavy-metal (HM) interfaces is important. Here we report the full angular dependence of the harmonic Hall voltages in a predominantly easy-plane AFM, epitaxial *c*-axis oriented α-Fe_2O_3 films, with an interface to Pt. By modeling the harmonic Hall signals together with the α-Fe_2O_3 magnetic parameters, we determine the amplitudes of fieldlike and dampinglike SOTs. Out-of-plane field scans are shown to be essential to determining the dampinglike component of the torques. In contrast to ferromagnetic–heavy-metal heterostructures, our results demonstrate that the fieldlike torques are significantly larger than the dampinglike torques, which we correlate with the presence of a large imaginary component of the interface spin-mixing conductance. Our work demonstrates a direct way of characterizing SOTs in AFM-HM heterostructures.

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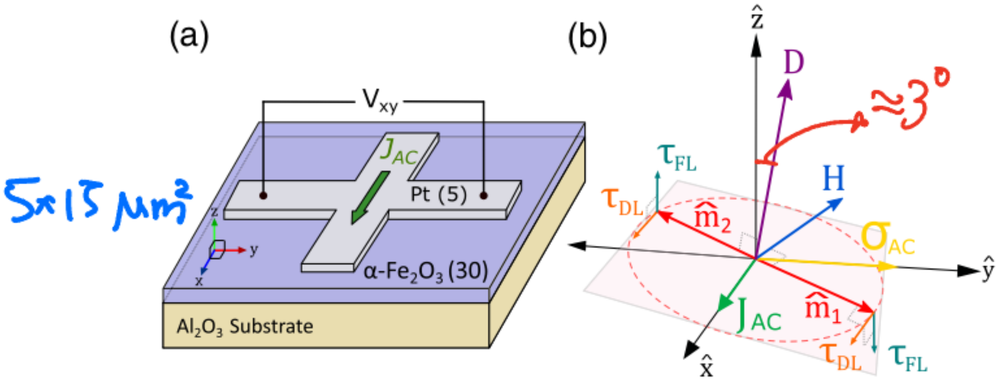
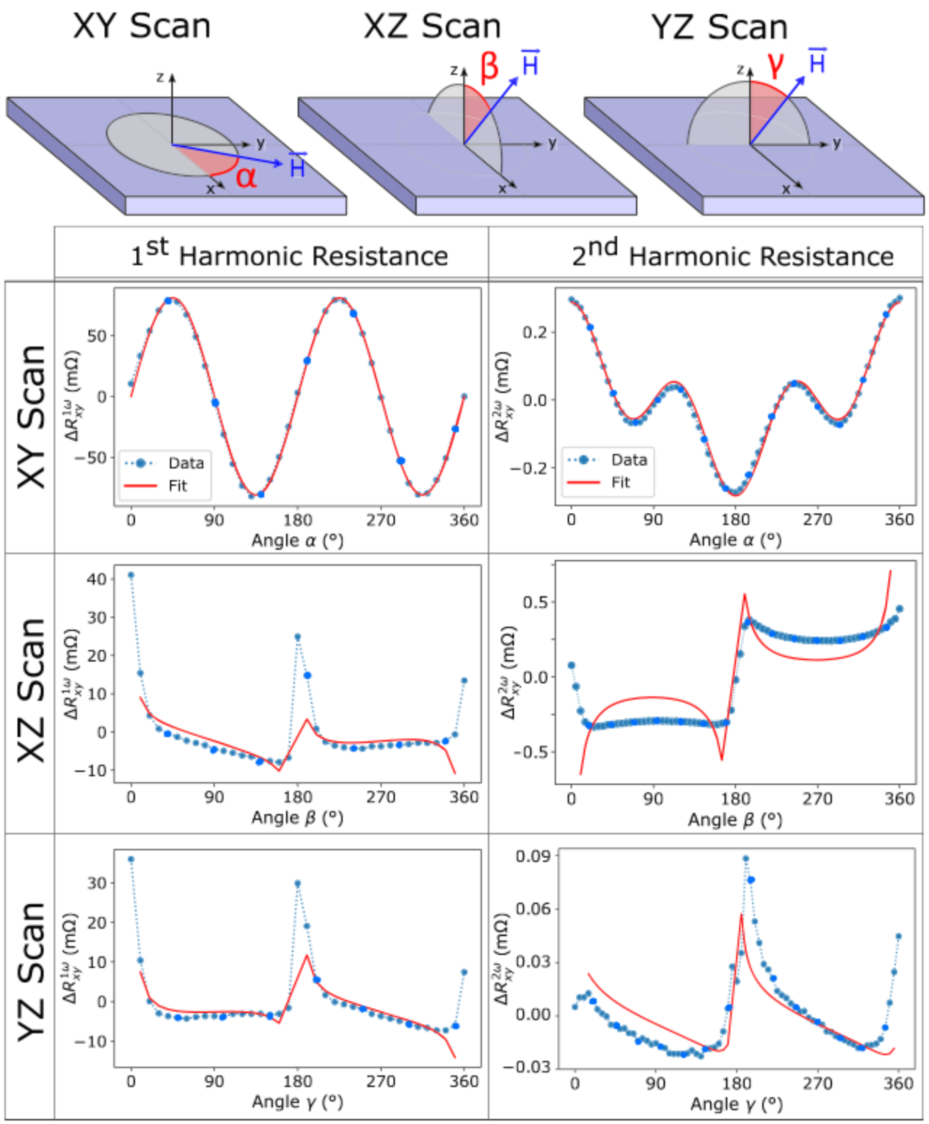
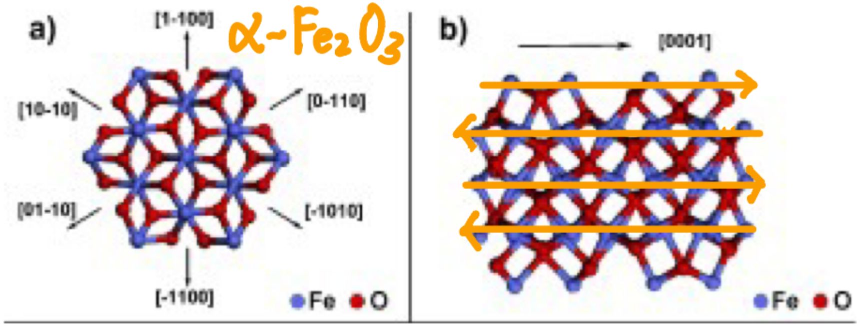




We fit the experimental results with three free parameters: the direction of the hard axis ($\boldsymbol{e}_h$) and the amplitudes of the spin-orbit torques (H_{FL} and H_{DL}). For every scan, first we fit the first harmonic response, where we extract the current-independent constant R_0 [Eq. (4)]. Then together with the R_0, we use material parameters from the literature $H_D = 2\,\mathrm{T}$, $H_K = 0.01\,\mathrm{T}$, and $H_{\mathrm{ex}} = 900\,\mathrm{T}$ [36–38], to fit the responses with our model. These fits allow us to extract the amplitudes of effective fields associated with the spin-orbit torques per current density which are $H_{\mathrm{FL}}/J_{\mathrm{ac}} \approx 7.5 \times 10^{-2}\,\mathrm{T}/(10^{12}\,\mathrm{A/m^2})$ and $H_{\mathrm{DL}}/J_{\mathrm{ac}} \approx 4.2 \times 10^{-4}\,\mathrm{T}/(10^{12}\,\mathrm{A/m^2})$.

A slight tilting ($\sim 3°$) of the hard-axis $\boldsymbol{e}_h$ f



Enhanced second harmonic Hall resistance in in-plane synthetic antiferromagnets

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Libai Zhu, Xiaoguang Xu,[a)] Tanzhao Zhang, Mengxi Wang, Kangkang Meng,[a)] Yong Wu, Jikun Chen, and Yong Jiang[a)]

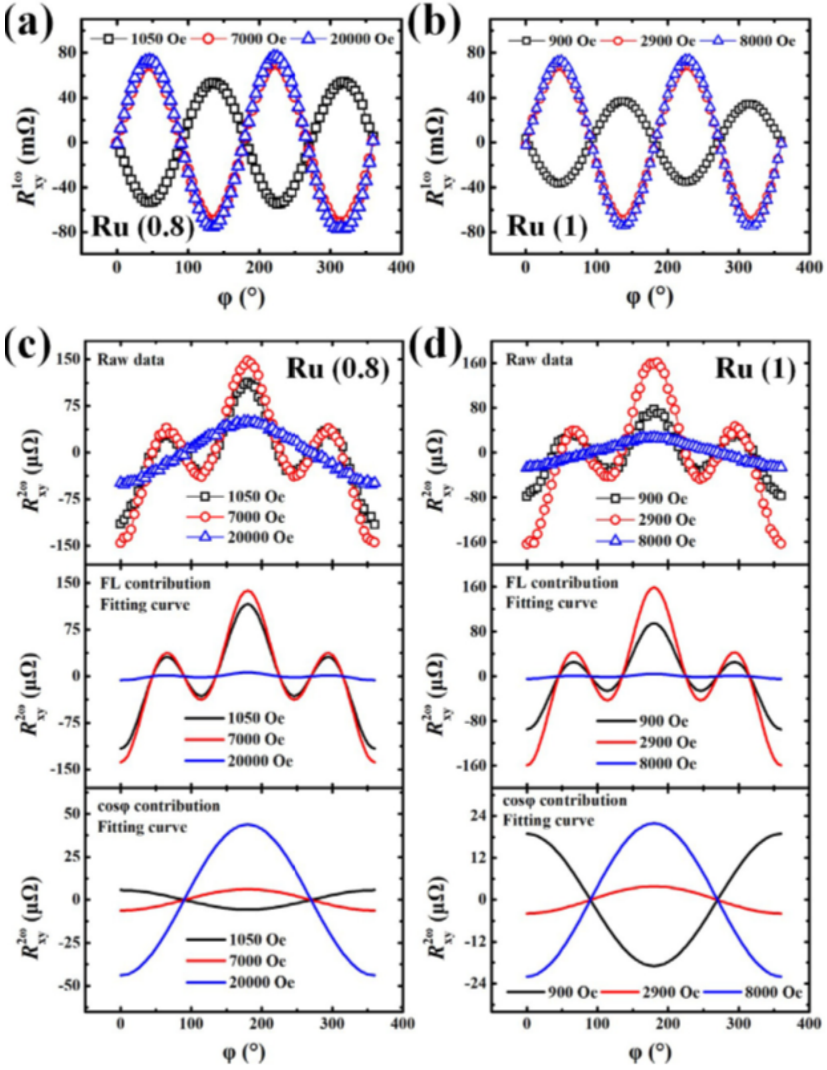
AFFILIATIONS

School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

[a)]Authors to whom correspondence should be addressed: xgxu@ustb.edu.cn; kkmeng@ustb.edu.cn; and yjiang@ustb.edu.cn

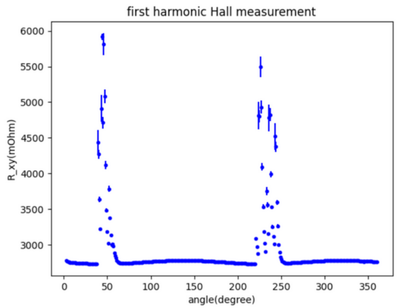
ABSTRACT

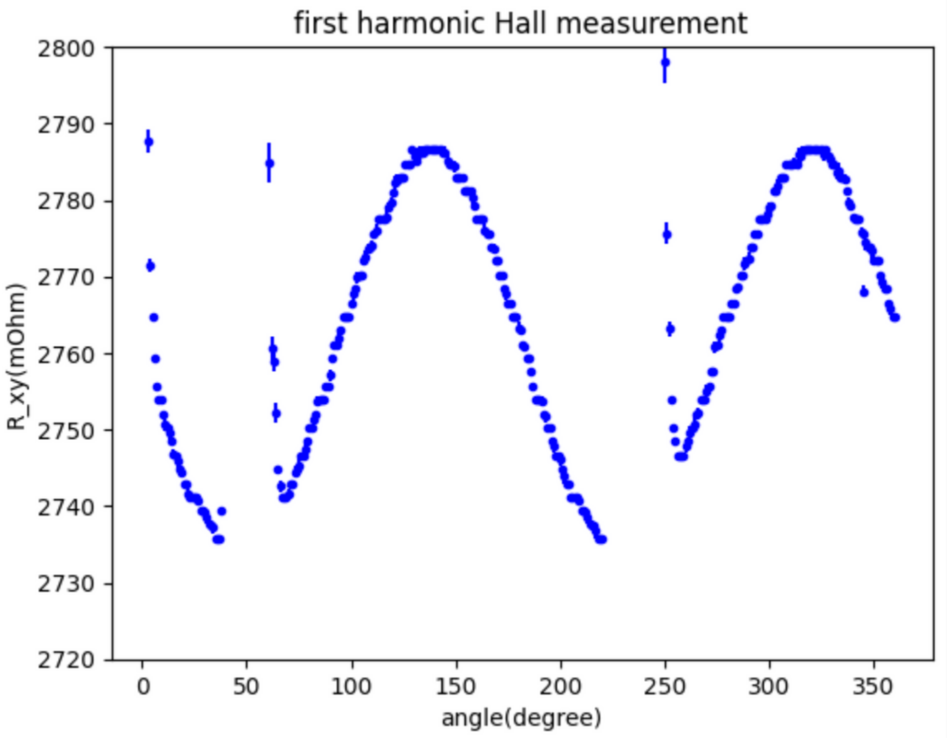
Synthetic antiferromagnet (SyAF) has been demonstrated to be an ideal candidate for spin–orbit torque (SOT) based spintronic devices. However, the detailed mechanism needs to be clarified due to the coexistence of multiple effects. This paper studies SOT and the thermoelectric effect in SyAF of Pt/Co/Ru/Co/Pt by harmonic Hall resistance measurements. Different from the traditional Co/Pt bilayers, the second harmonic Hall resistance signals of the SyAF-based devices are obviously enhanced under a large external magnetic field (B_{ext}), which is caused by the antiferromagnetic exchange coupling fields weakening the influence of B_{ext}. By fitting the Hall resistance curves, the field-like torque is demonstrated to be the main contribution to the Hall resistance. Interestingly, both the SOT effective fields are greatly enhanced for antiparallel alignment. This study separates the contributions of SOT and the thermoelectric effect in the SyAF structures and enables the design of the spintronic devices with stability under a large magnetic field.

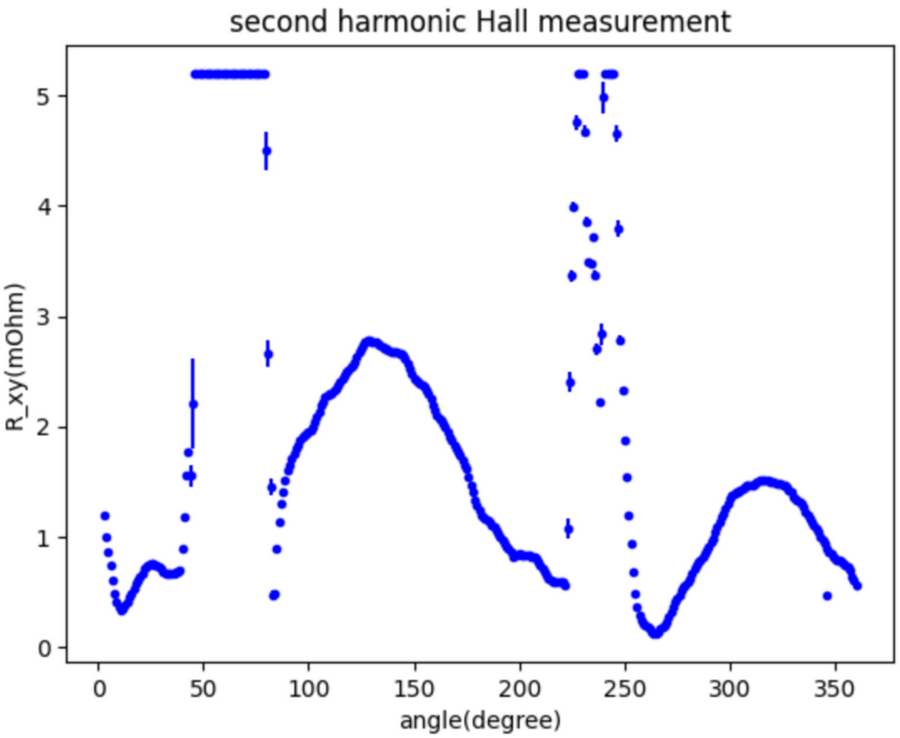


guess for $NiPS_3$

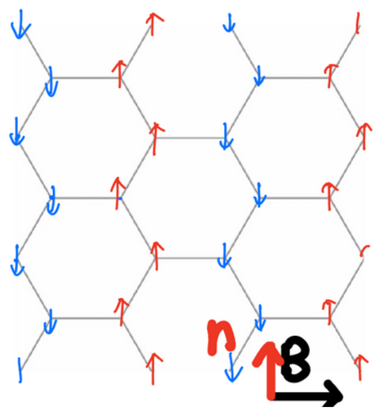
$$I_0 = 2.97mA$$
$$f = 953Hz$$
$$H = 5T$$
$$t_{Pt} = 10nm$$

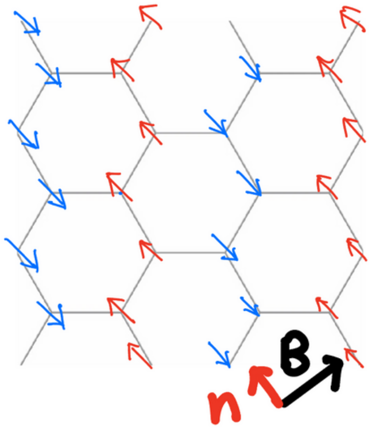


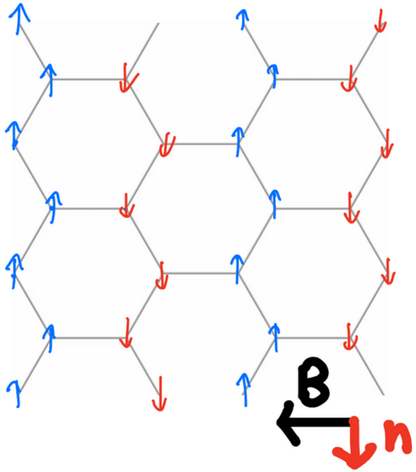




1st harmonic shows Neel vector can point at any direction





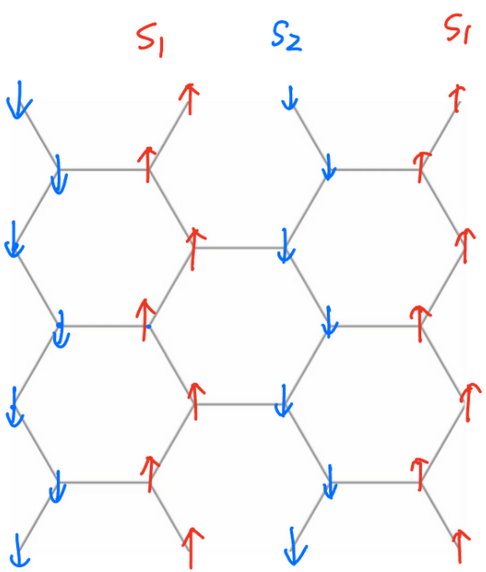


S_i^2 $\quad$ $S_1 \cdot S_2$

J_1 $\quad 2 \upuparrows \quad 1 \uparrow\downarrow$

J_2 $\quad 2 \upuparrows \quad 4 \uparrow\downarrow$

J_3 $\quad\quad\quad 3 \uparrow\downarrow$



interation

hexagon #

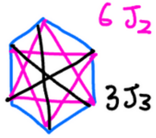
$J_1 : \frac{3N}{2}$

$J_2 : \boxed{\frac{N}{2}} \cdot 6 = 3N$

$J_3 : \boxed{\frac{N}{2}} \cdot 3 = \frac{3N}{2}$

average over $\frac{N}{2}$

$\Rightarrow 3J_1 + 6J_2 + 3J_3$



$$\Rightarrow \underbrace{(J_1 + 4J_2 + 3J_3)}_{H_E} S_1 \cdot S_2 + \cancel{(2J_1 + 2J_2) S_1^2}$$