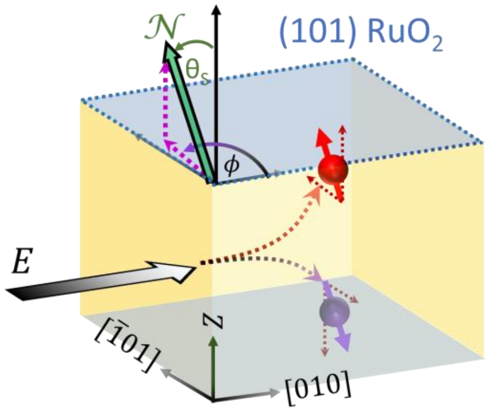
Generation of tilted spin current by the collinear antiferromagnet RuO_2



A. Bose et. al. Nat. Electron. 5, 267 (2022)

Arnab Bose

Johannes Gutenberg Universität Mainz, Germany (M. Kläui's group)

Cornell University, NY, US

H. Nair, N. Schreiber, D. Schlom (RuO_2) and J. Sun (IrO_2), J. Nelson
Cornell, Material Science

X. Zhang, D. Muller (STEM), *Cornell AEP*

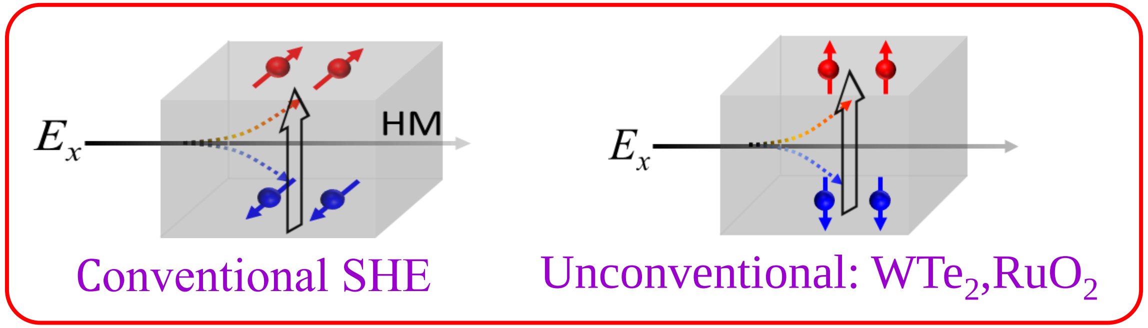
D.-F. Shao, E. Tsymbal, (DFT calculations)
University of Nebraska–Lincoln

R. Jain, D. Ralph and R. Buhrman, *Cornell*

Outlines

Background and motivation

- Conventional vs unconventional spin current

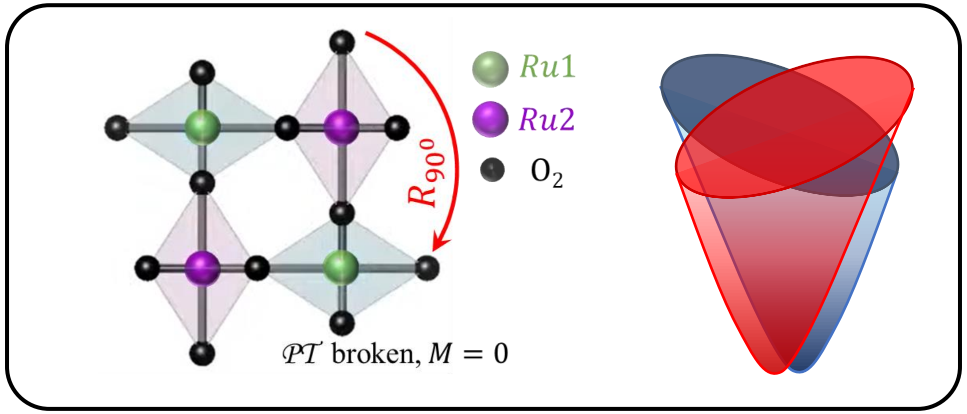


Measurement techniques

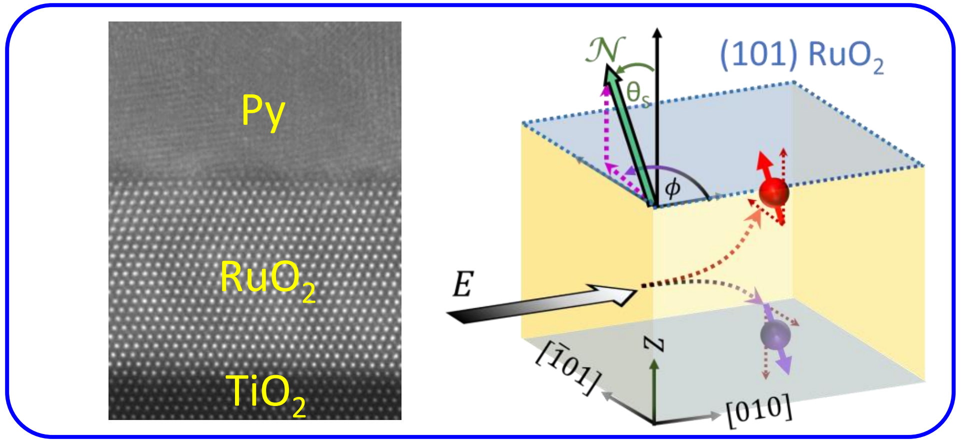
- ST-FMR (*PRL106, 036601 (2011)*)
- In-plane 2nd harmonics Hall (*PRB **89**, 144425 (2014)*)

Band structure of RuO_2 (*arXiv: 2204.10844v1 (2022)*)

- Spin-split bands contributing to exotic electronic transport properties

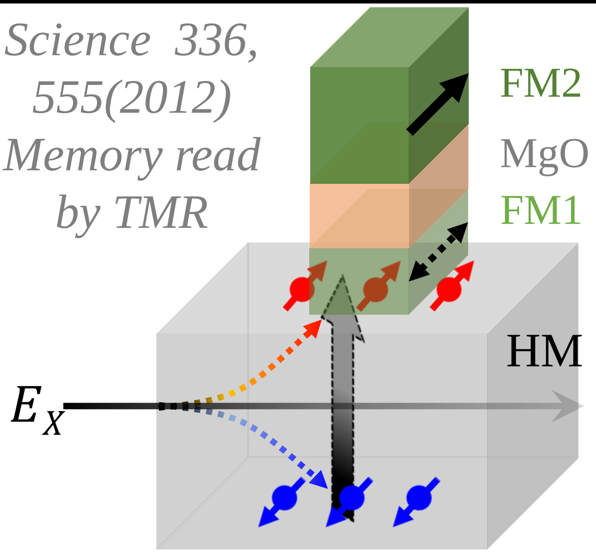


Experimental detection of the "*tilted spin current*" in RuO_2 (*Nat. Electron. 5, 267 (2022)*)



Spin-orbit torques

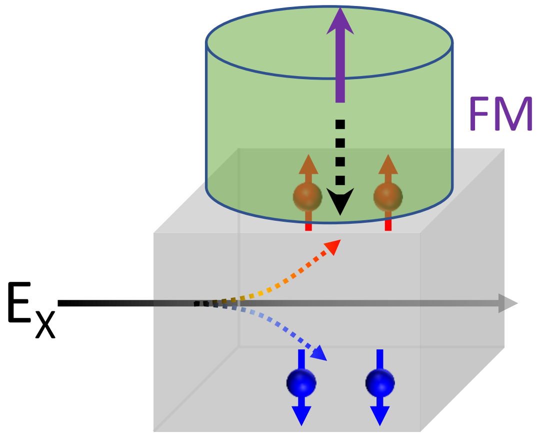
Science 336, 555(2012)
Memory read by TMR



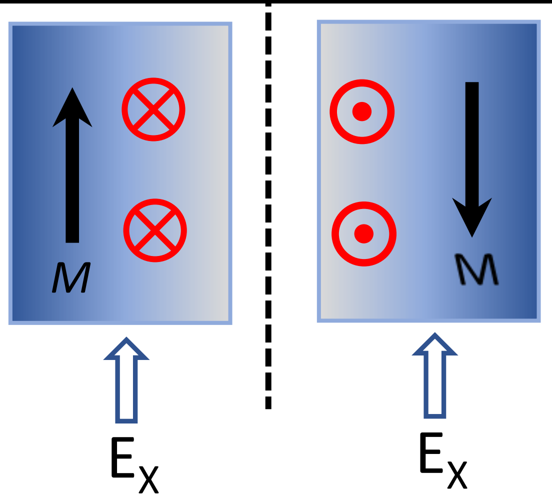
Spin Hall effect (SHE)

LLGS Equation
(JMMM 159, L1 (1996))

$$\frac{d\hat{m}}{dt} = -\gamma(\hat{m} \times \vec{H}_{net}) + \alpha\gamma(\hat{m} \times \vec{H}_{net} \times \hat{m}) + \Gamma_{FL}(\hat{m} \times \sigma_y) + \Gamma_{DL}(\hat{m} \times (\sigma_y \times \hat{m}))$$



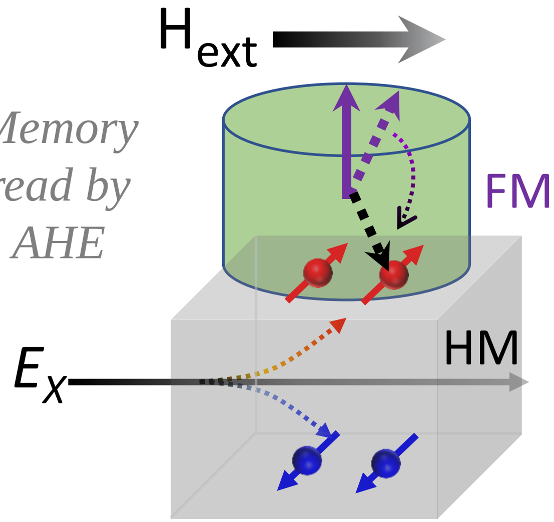
Unconventional spin-current (op-DL)



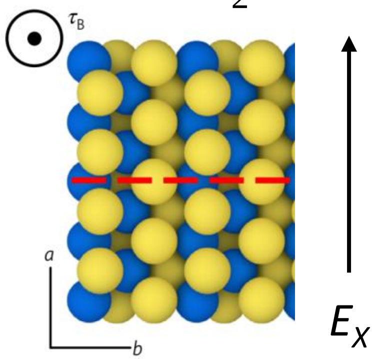
Mirror symmetry ⊥ to E_X to be broken

M-dependent SHE / Magnetic SHE/
Interface generated J_S
(RMP 91, 035004 (2019))

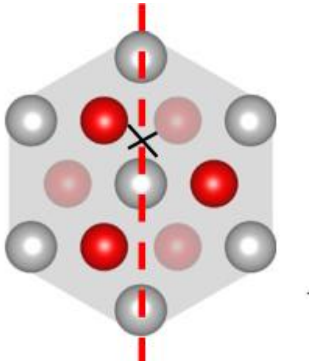
Memory read by AHE



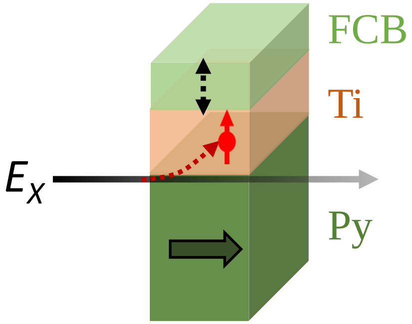
Nature 476, 189 (2011), PRL 109, 096602 (2012)



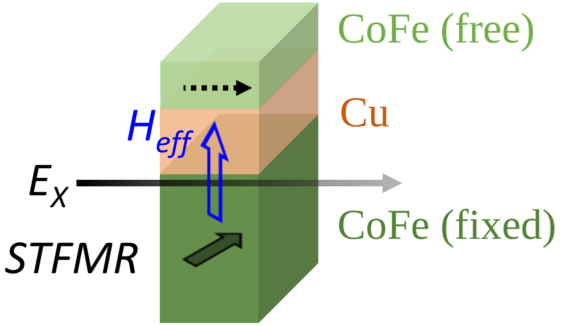
Nat. Phys. 13, 300 (2017)



Nat. Nano. 16, 277 (2021)

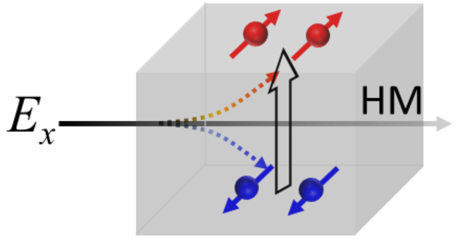


Nat. Mater. 17, 509 (2018)

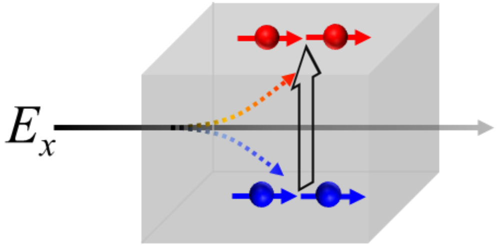


A. Bose et. al. PRAppl 9, 064026 (2018)

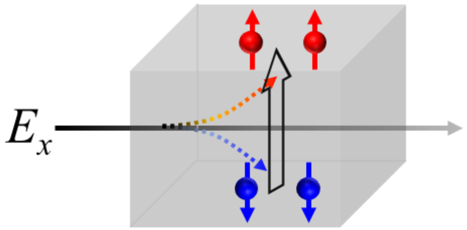
Types of SOT and measurement techniques



SHE, *REE* etc.



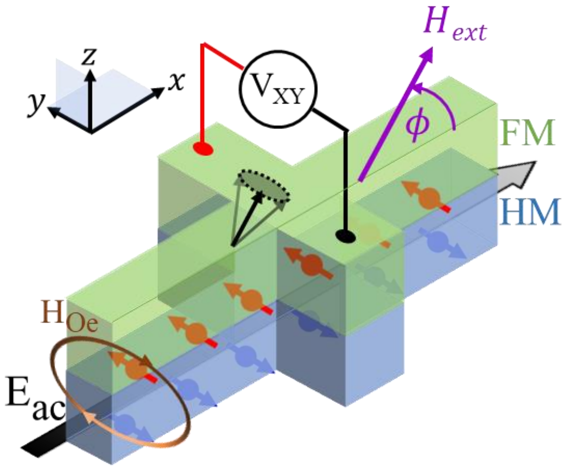
(Dresselhaus etc.)



(Unconventional, WTe_2, RuO_2)

$$\Gamma_{DL} \rightarrow (m \times \sigma_{z,x}^{X,Y,Z} \times m)$$
$$\Gamma_{FL} \rightarrow (m \times \sigma_{z,x}^{X,Y,Z})$$

In-plane 2nd Harmonic Hall

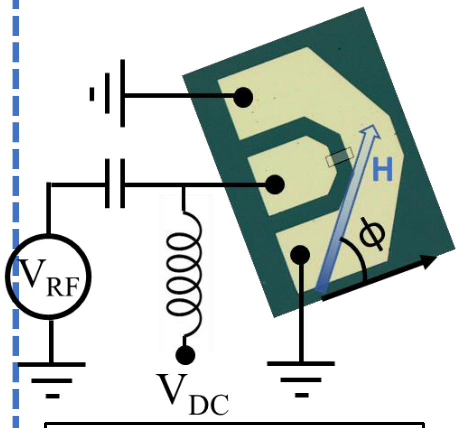


$$\tau_{ip} \rightarrow \overrightarrow{R_{AHE}(t)} \rightarrow \overrightarrow{M(t)} \times \overrightarrow{H_{eff}(t)}$$
$$\tau_{op} \rightarrow : \overrightarrow{E_{PHE}(t)} \rightarrow \overrightarrow{M(t)} \times \overrightarrow{H_{eff}(t)} \times \overrightarrow{M(t)}$$

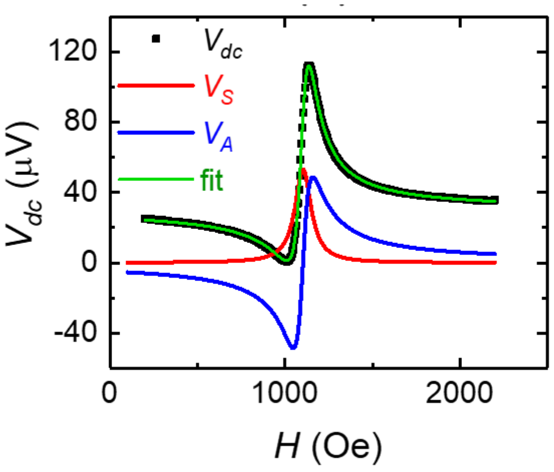
$$V_{XY}^{2\omega} \rightarrow \begin{cases} D_{DL}^{Y} \cos\phi + F_{FL}^{Y} \cos\phi \cos 2\phi \\ +D_{DL}^{X} \sin\phi + F_{FL}^{X} \sin\phi \cos 2\phi \\ +D_{DL}^{Z} \cos 2\phi + F_{FL}^{Z} \end{cases}$$

Constants D and F depend on H_{ext}

ST-FMR



$V_{dc} \rightarrow \langle I_{rf}(t).R_{rf}^{amr}(t)\rangle$



$$V_S = S\left(\frac{\Delta^2}{(H - H_0)^2 + \Delta^2}\right) \qquad V_A = A\left(\frac{(H - H_0)\Delta}{(H - H_0)^2 + \Delta^2}\right)$$

In-plane torques — Out-plane torques

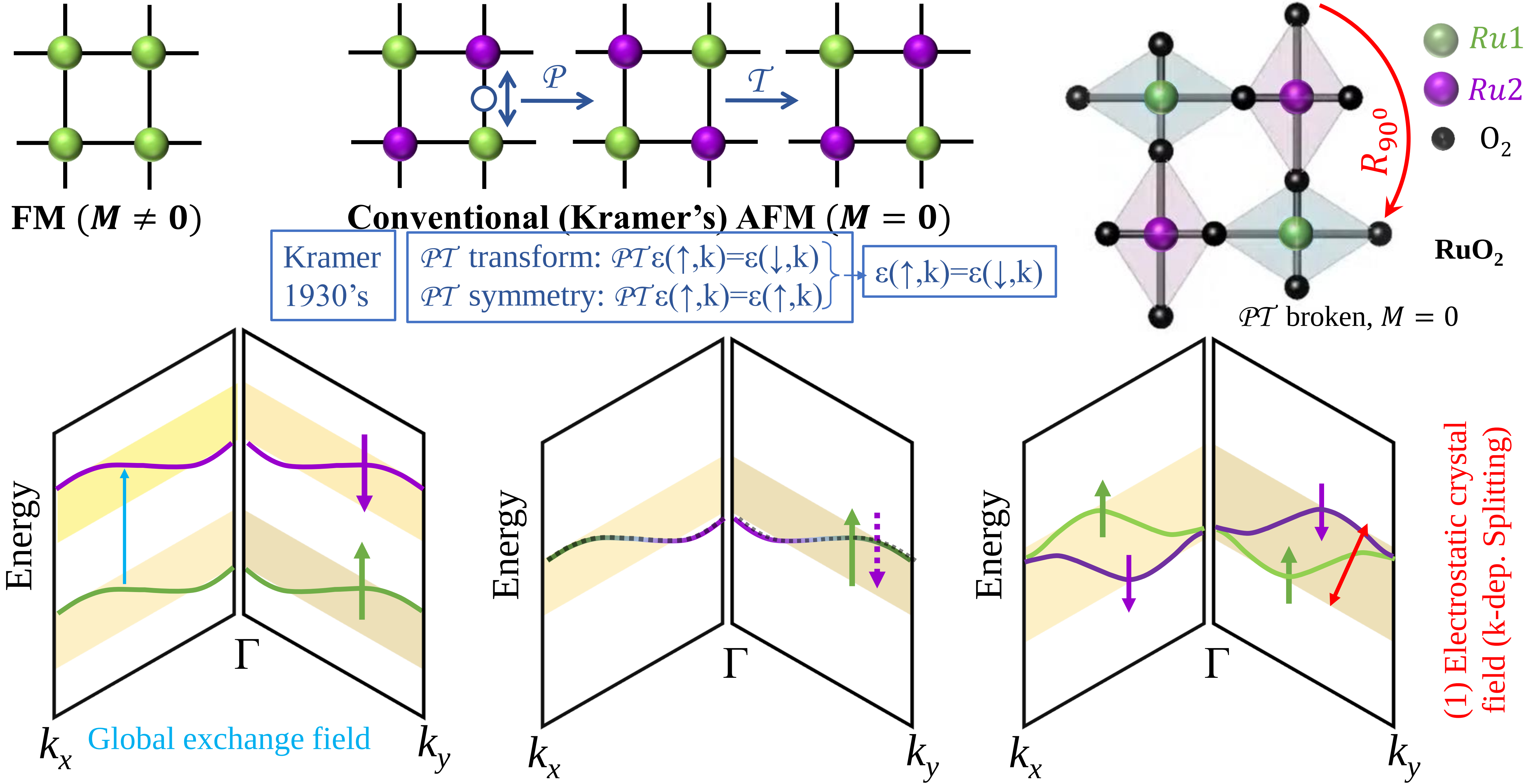
$\{m \times (\sigma_{z,x}^{Y} \times m)\}$ $\{m \times (\sigma_{z,x}^{X} \times m)\}$ $\{m \times \sigma_{z,x}^{Z}\}$

$$S = S_{DL}^{Y} \cos\phi \sin 2\phi + S_{DL}^{X} \sin\phi \sin 2\phi + S_{FL}^{Z} \sin 2\phi$$
$$A = A_{FL}^{Y} \cos\phi \sin 2\phi + A_{FL}^{X} \sin\phi \sin 2\phi + A_{DL}^{Z} \sin 2\phi$$

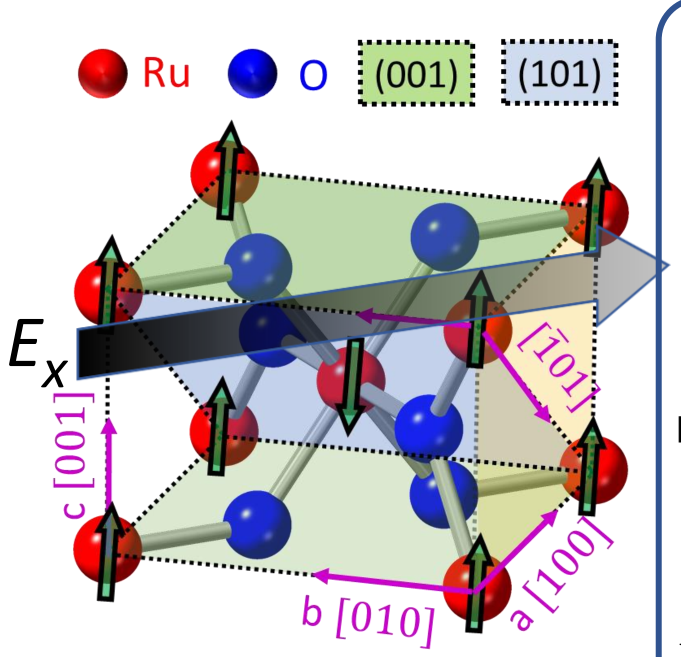
$\{m \times \sigma_{z,x}^{Y}\}$ $\{m \times \sigma_{z,x}^{X}\}$ $\{m \times (\sigma_{z,x}^{Z} \times m)\}$

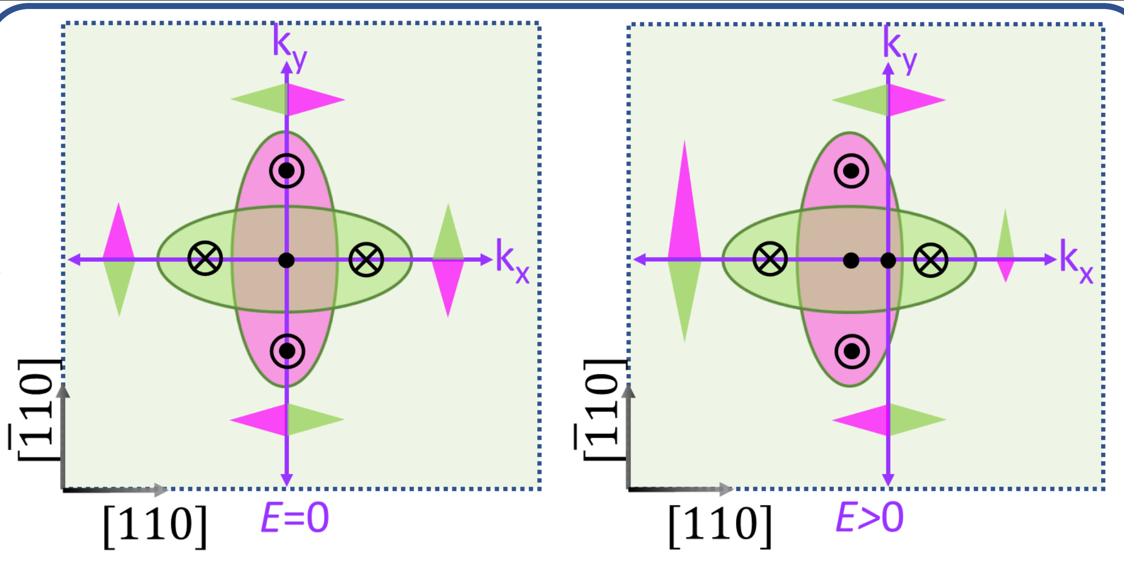
[*PRB* **89**, *144425 (2014),* *arXiv:2108.09150 (2021)*] [*PRL106, 036601 (2011)*]

RuO_2: spin-split bands (*arXiv:2105.05820*)



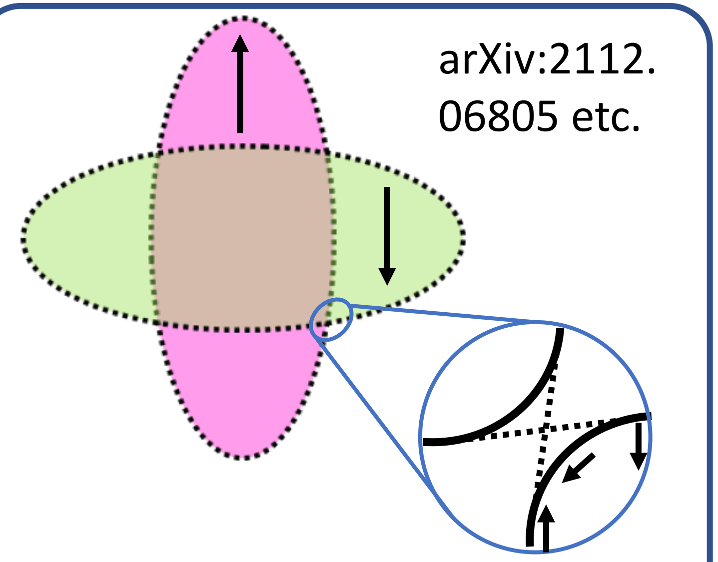
Electronics with the altermagnet (RuO_2) (Šmejkal et. al. arXiv:2204.10844)





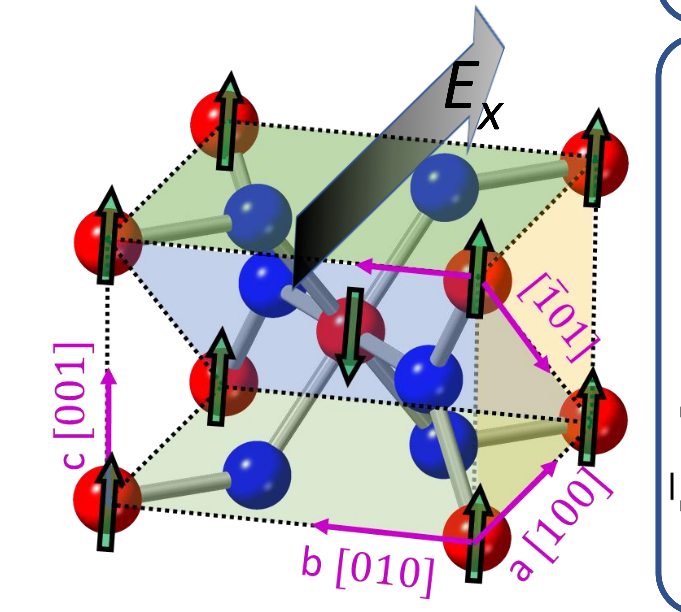
(1) Spin polarized current when E→[110]

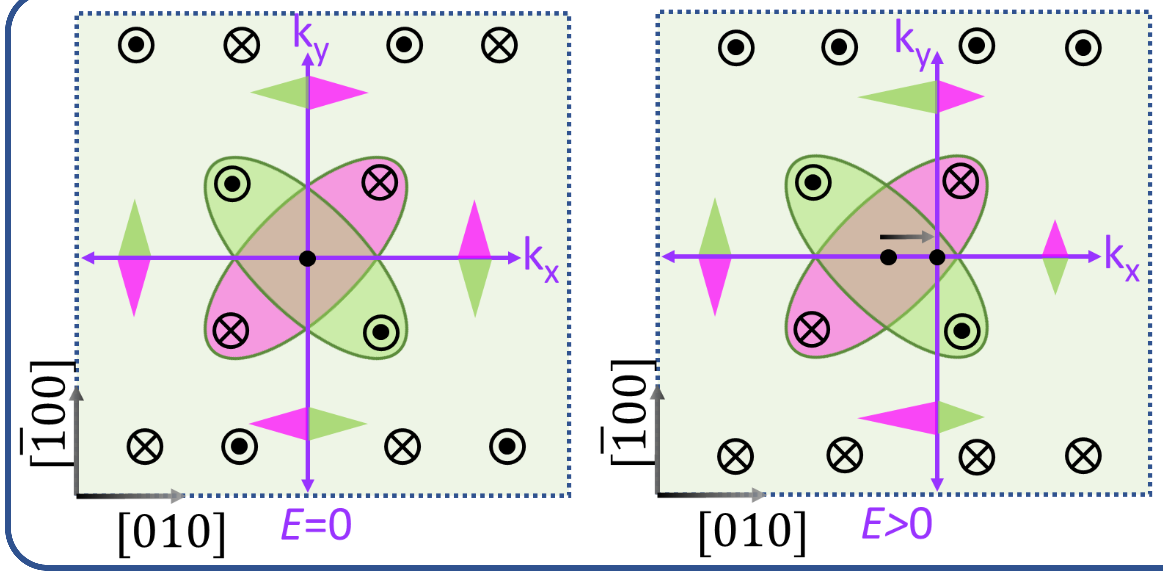
Nat Comm 12, 7061 (2021), Phys Rev X 12, 011028 (2021)



(2) Crystal axis dependent AHE

Sci Adv. 6, eaaz8809 (2020)





(3)

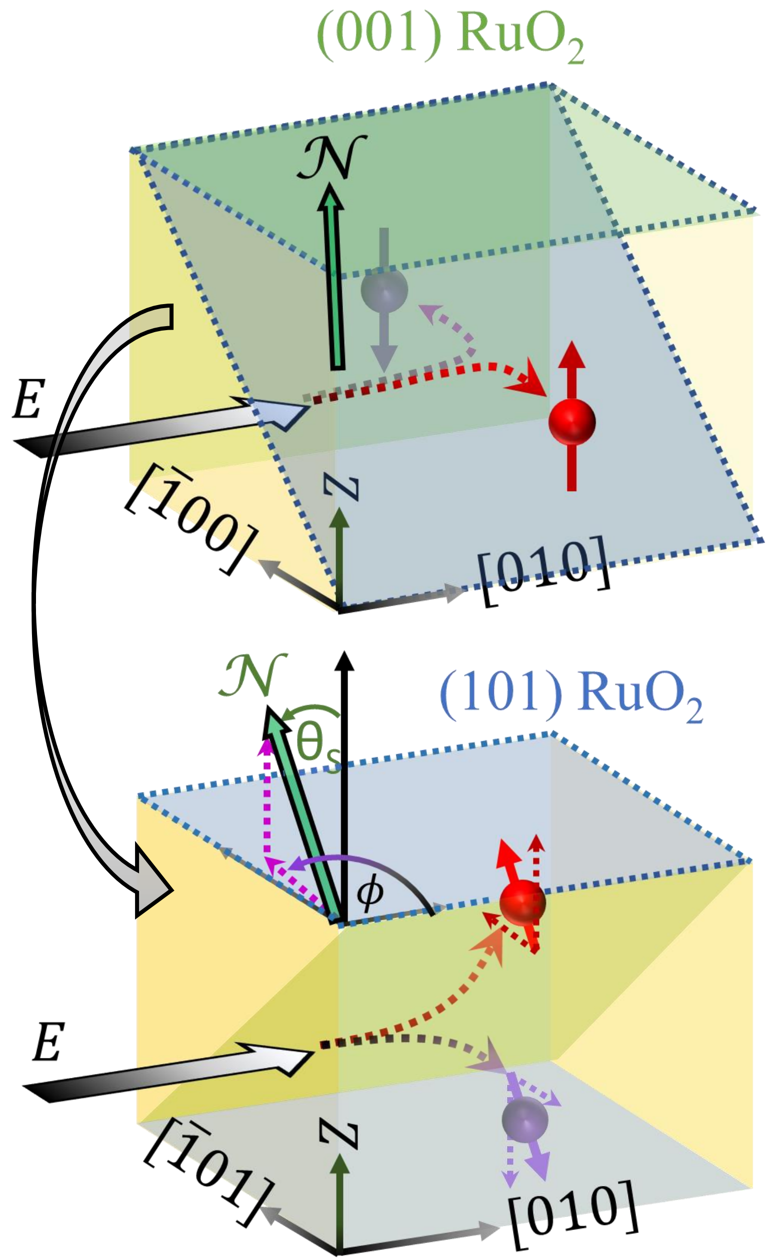
Transverse pure J_S from spin-split bands, polarized along $\vec{N}$

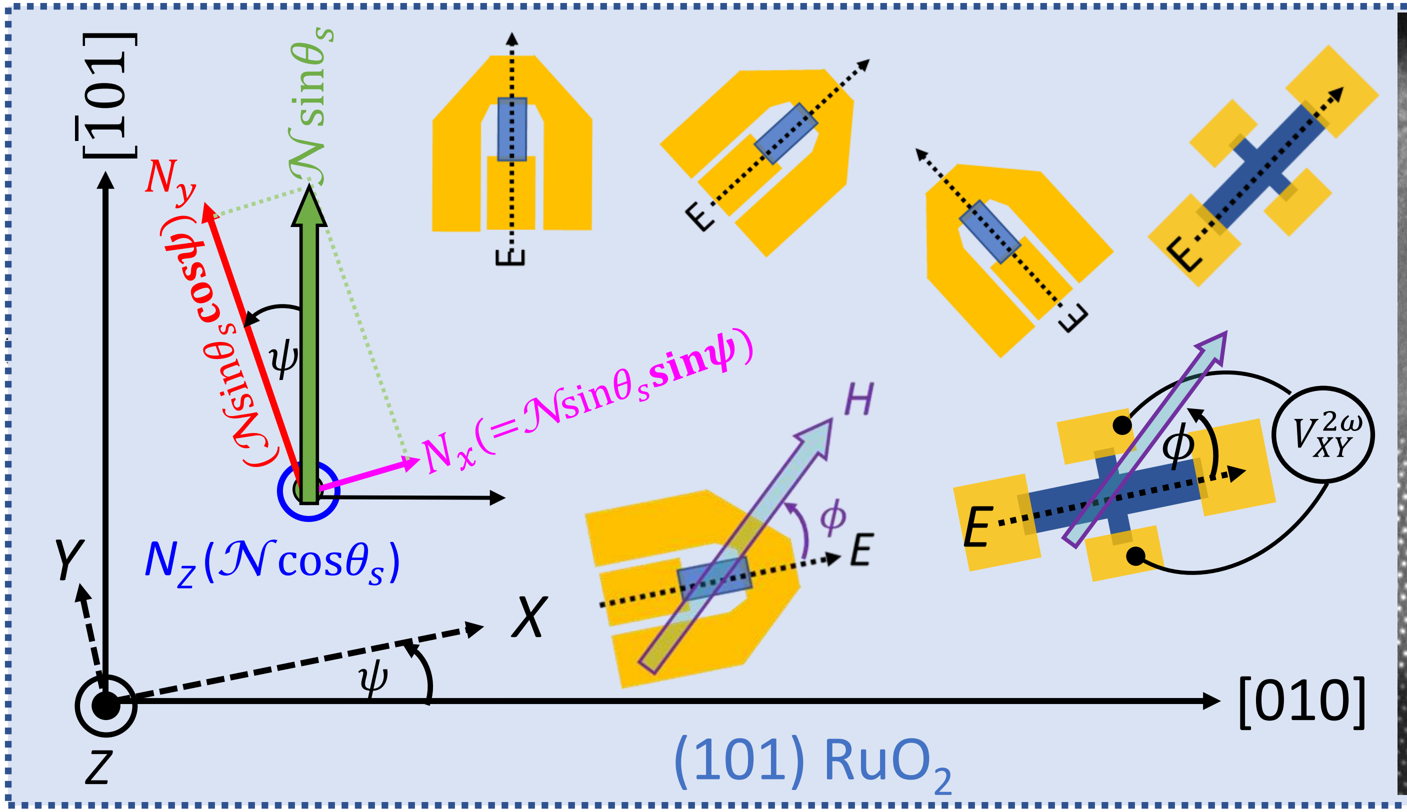
Theory: *PRL 126, 127701 (2021)*

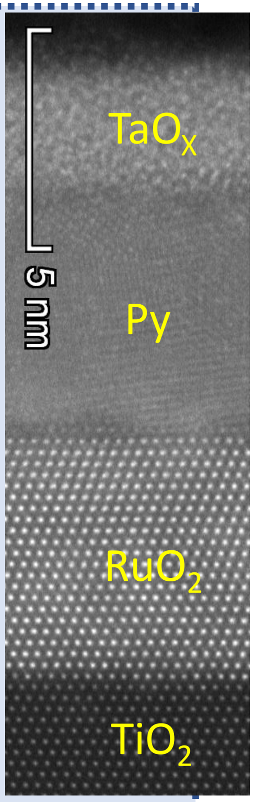
Exp: A. Bose. et. al. *Nat. Electron. 5, 267 (2022)*

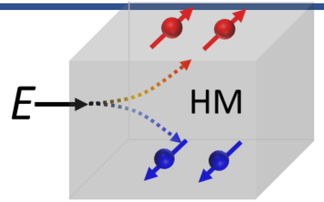
How to detect it?

Tilted spin-current generated by RuO_2 (*A. Bose et. al. Nat. Elecl.5, 267 (2022)*)



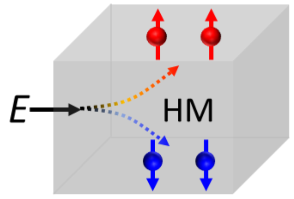


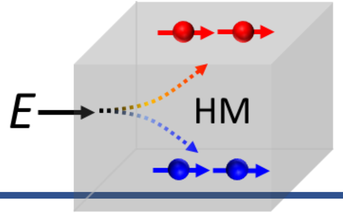




$$\xi^{Y}_{DL,E} = C_1.\ \sin\theta_s(\sin\theta_s \cos\psi)\cos\psi + C_0$$

$$\xi^{Z}_{DL,E} = C_1.\ \sin\theta_s\ (\cos\theta_s)\cos\psi$$





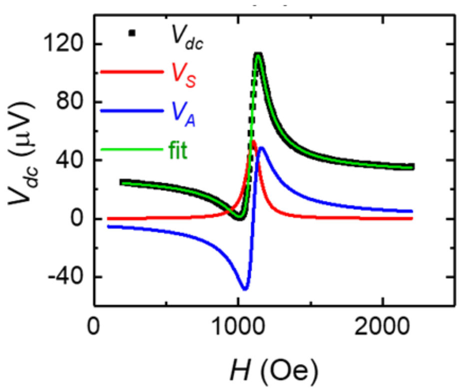
$$\xi^{X}_{DL,E} = C_1.\ \sin\theta_s(\sin\theta_s \sin\psi)\cos\psi$$

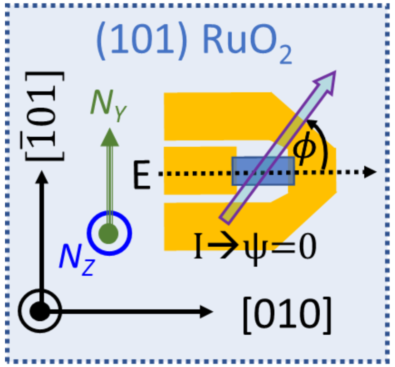
Spin-torque measurements by ST-FMR and SHH

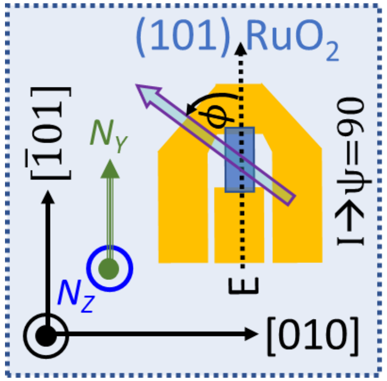
$$V_S = S\left(\frac{\Delta^2}{(H-H_0)^2+\Delta^2}\right) \qquad S = (S_{DL}^{Y}\cos\phi + S_{DL}^{X}\sin\phi + S_{FL}^{Z})\sin 2\phi$$

$$V_A = A\left(\frac{(H-H_0)\Delta}{(H-H_0)^2+\Delta^2}\right) \qquad A = (A_{FL}^{Y}\cos\phi + A_{FL}^{X}\sin\phi + S_{FL}^{Z})\sin 2\phi$$

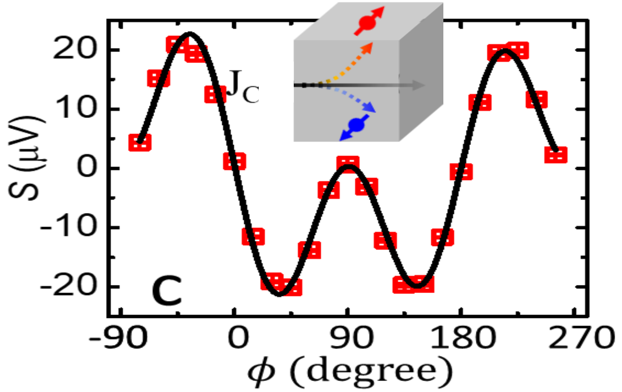
$$V_{XY}^{2\omega} = C + D_{DL}^{Y}\cos\phi + F_{FL}^{Y}\cos\phi\cos 2\phi + D_{DL}^{Z}\cos 2\phi + F_{FL}^{X}\sin\phi\cos 2\phi + D_{DL}^{Y}\sin\phi$$



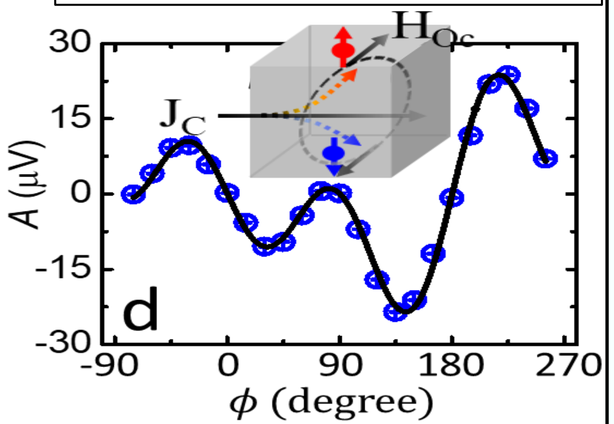




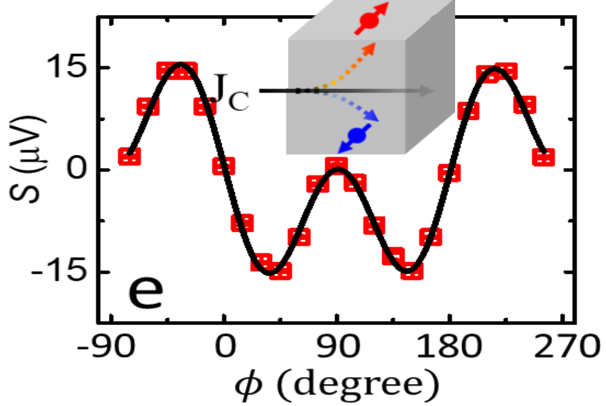
(SHE) $S_{DL}^{Y}\cos\phi\sin 2\phi$



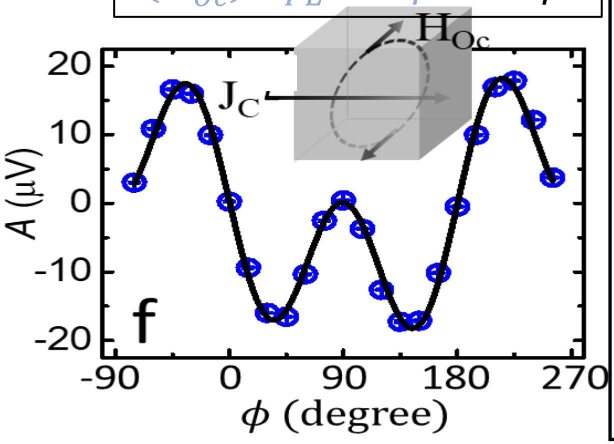
$(A_{FL}^{Y}\cos\phi + S_{FL}^{Z})\sin 2\phi$



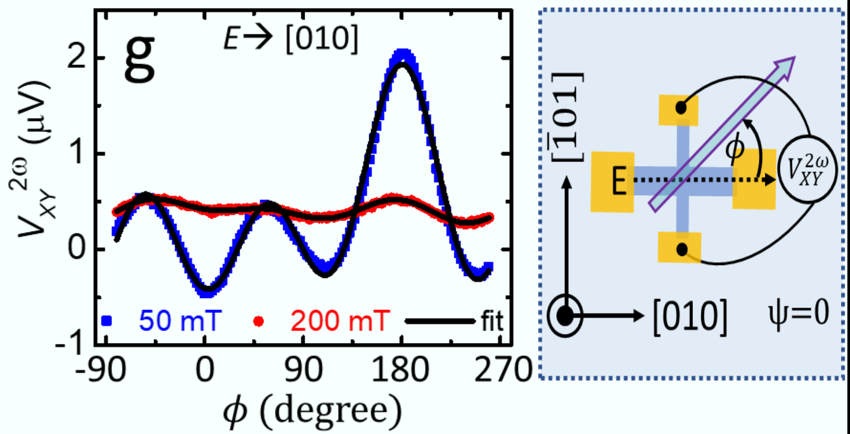
(SHE) $S_{DL}^{Y}\cos\phi\sin 2\phi$



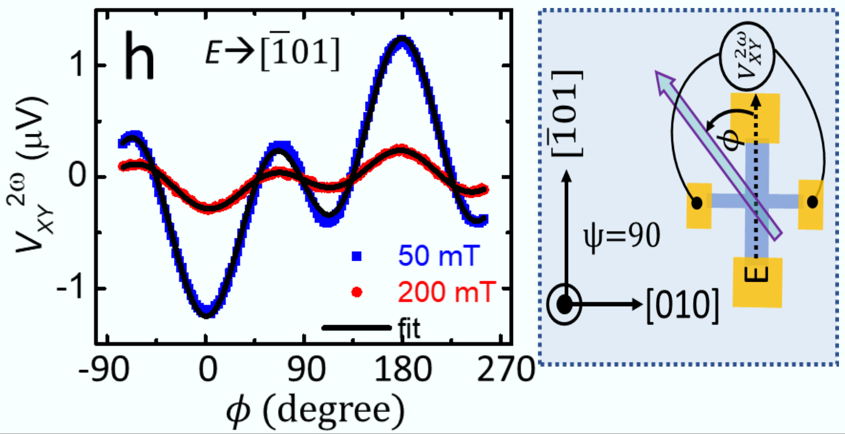
$(H_{Oe})\ A_{FL}^{Y}\cos\phi\sin 2\phi$



$D_{DL}^{Y}\cos\phi + F_{FL}^{Y}\cos\phi\cos 2\phi + D_{DL}^{Z}\cos 2\phi$



(SHE) $D_{DL}^{Y}\cos\phi + F_{FL}^{Y}\cos\phi\cos 2\phi\ (H_{Oe})$

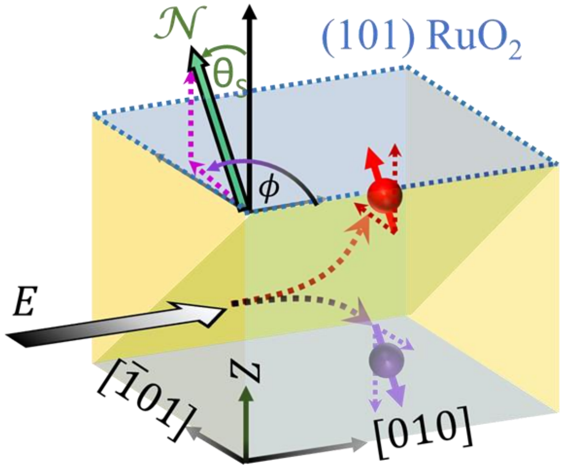


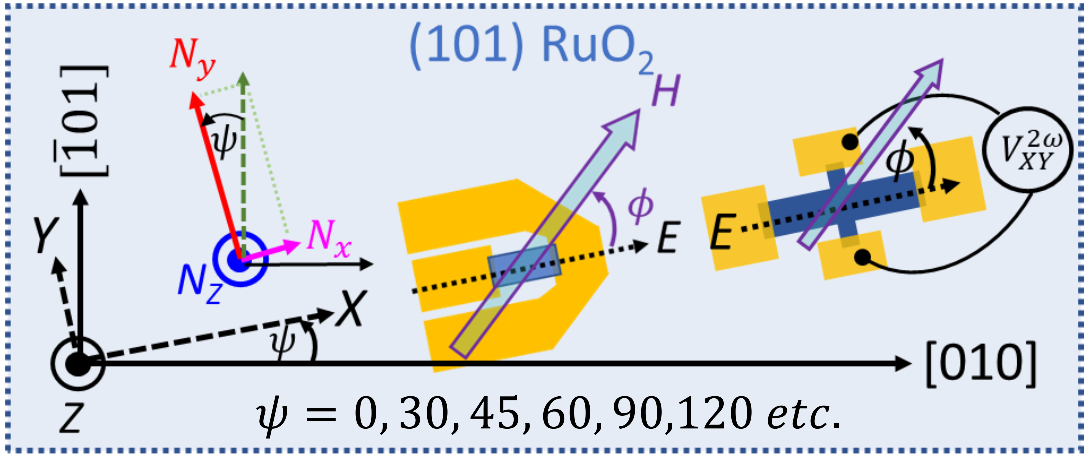
Detection of the tilted spin current in RuO_2

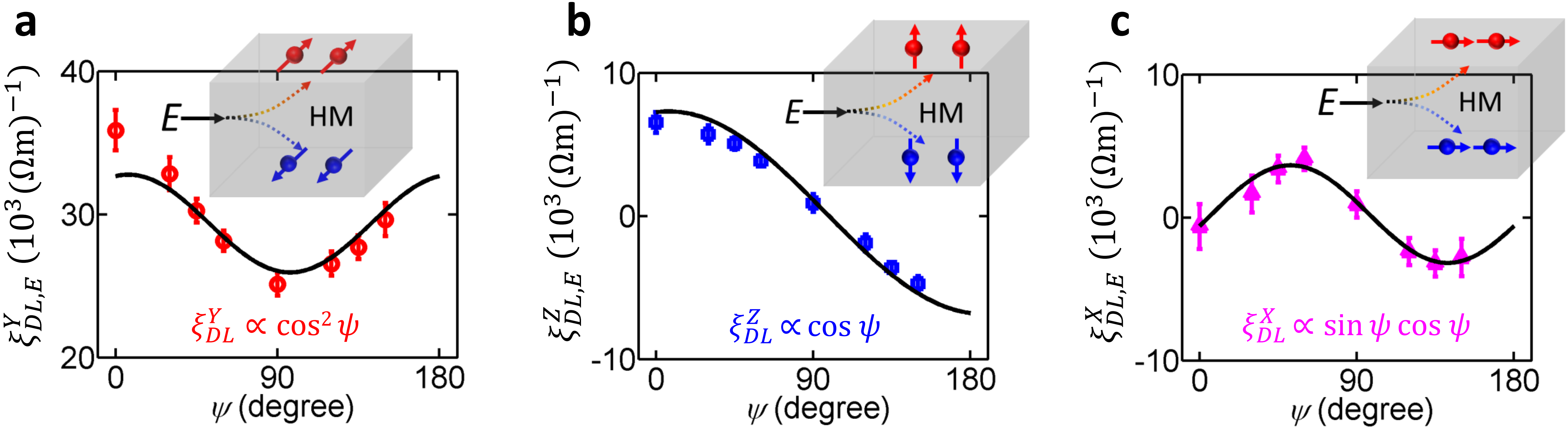
(A. Bose et. al. Nat. Electron. 5, 267 (2022))

S. Karube, et. al. arXiv:2111.07487

H. Bai, et. al. PRL 128, 197202 (2022)





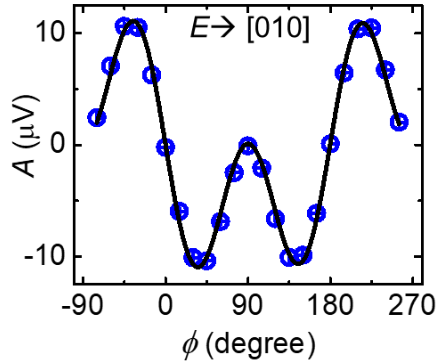


The tilted spin-current is a consequence of the novel spin-split bands of the emerging new type of anti-ferromagnet

A. Bose et. al. ACS Appl. Mater. Interfaces 12, 55411 (2020)

Additional experiments

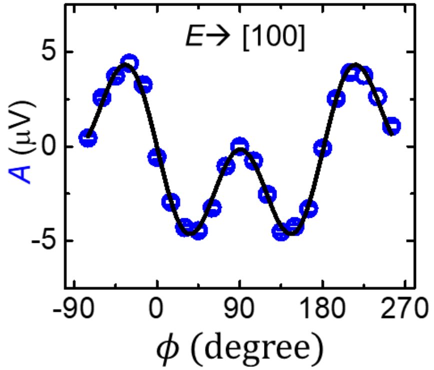
(a) (101)IrO_2/Py



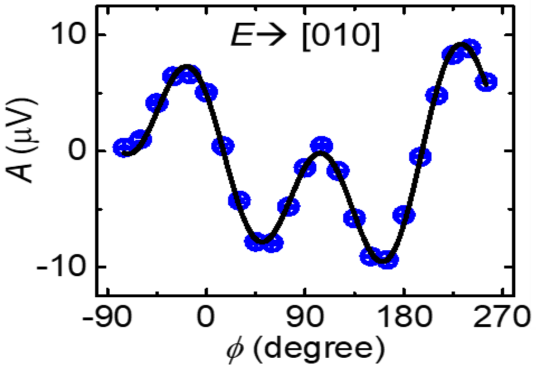
Isostructural

	RuO_2	IrO_2
a	4.543	4.545
b	4.543	4.545
c	3.140	3.190

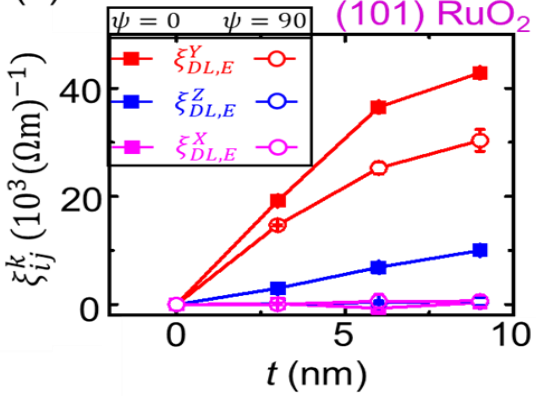
(b) (001)RuO_2/Py



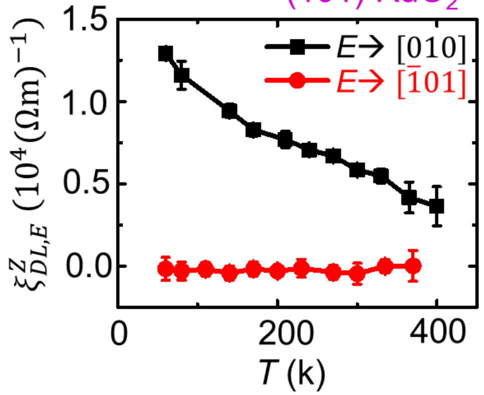
(c) (101) RuO_2/Ir/Py/Ir



(d) (101) RuO_2



(e) (101) RuO_2



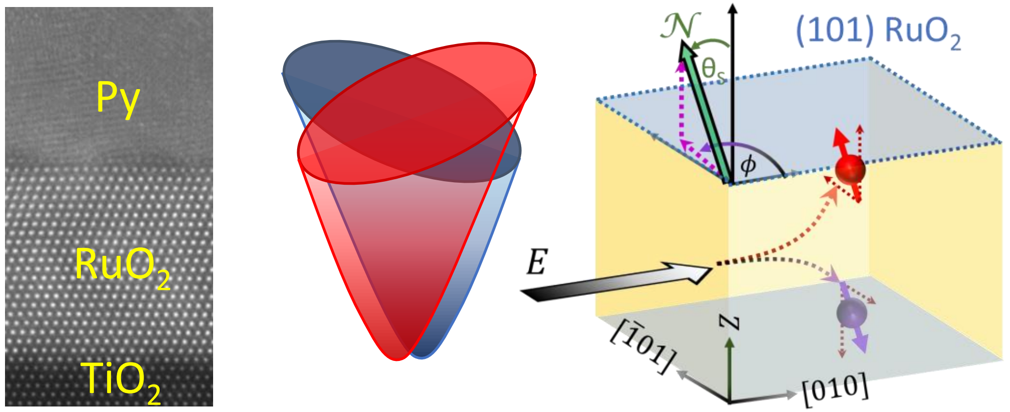
Summary

1. Isostructural (101) IrO_2 cannot produce op-DLT that (101) RuO_2 exhibits suggesting the importance of AF-ordering.

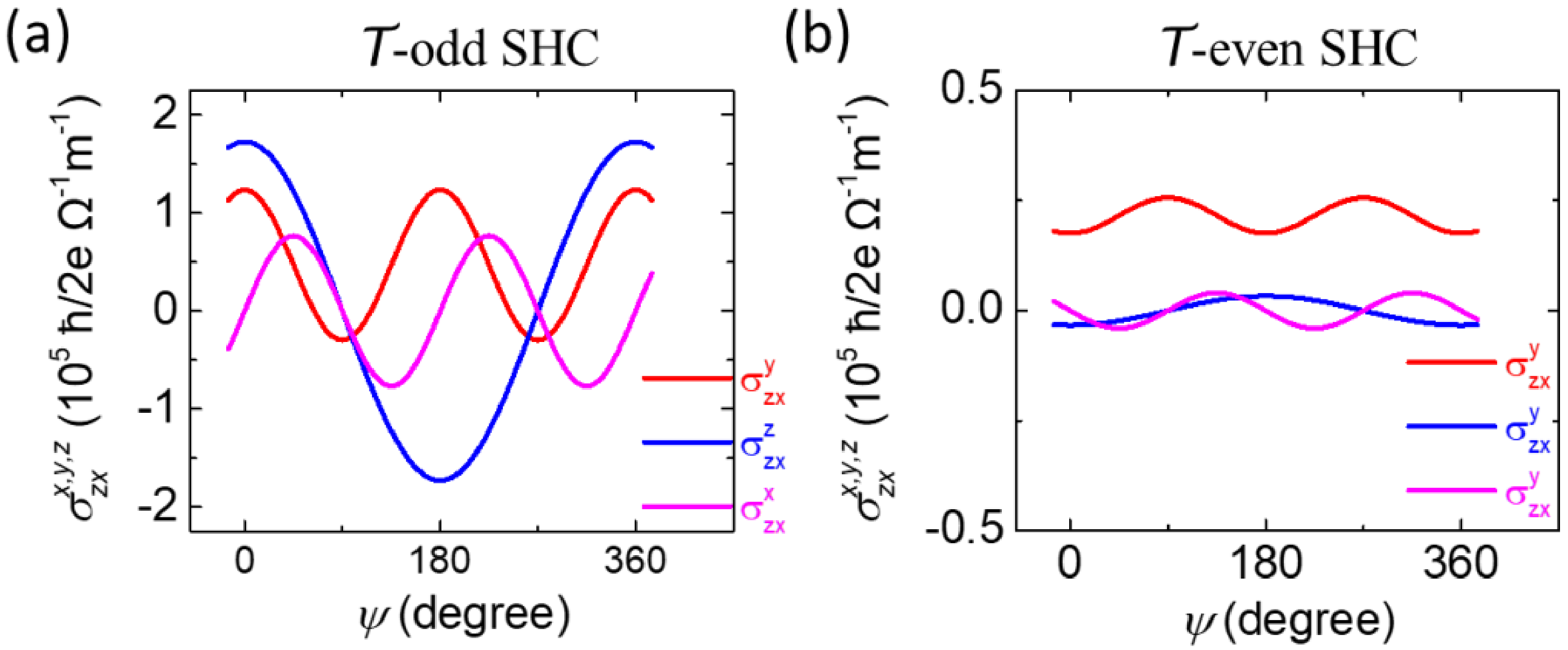
2. Strong dependence of OP-DLT with crystal axis and crystal planes.

3. Bulk origin of the spin current from RuO2 thickness dependence and Ir spacer insertion.

4. Signature of T-odd spin current from strong temperature dependence of op-DLT.



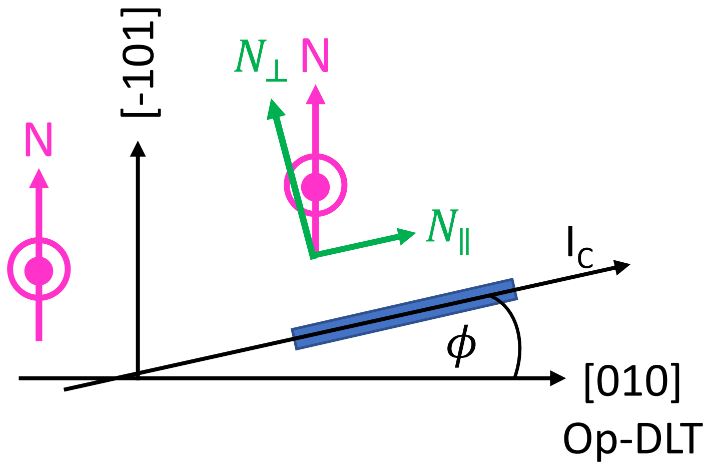
Predicted spin-Hall conductivities



$$\sigma_{ij}^{k} = -\frac{e\hbar}{\pi}\int \frac{d^3\vec{k}}{(2\pi)^3}\sum_{n,m}\frac{\Gamma^2 \mathrm{Re}\left(\langle n\vec{k}|J_i^k|m\vec{k}\rangle\langle m\vec{k}|v_j|n\vec{k}\rangle\right)}{\left[\left(E_F - E_{n\vec{k}}\right)^2 + \Gamma^2\right]\left[\left(E_F - E_{m\vec{k}}\right)^2 + \Gamma^2\right]},$$

$$\sigma_{ij}^{k} = -\frac{2e}{\hbar}\int \frac{d^3\vec{k}}{(2\pi)^3}\sum_{n'\neq n}\frac{\mathrm{Im}\left(\langle n\vec{k}|J_i^k|n'\vec{k}\rangle\langle n'\vec{k}|v_j|n\vec{k}\rangle\right)}{\left(E_{n\vec{k}} - E_{n'\vec{k}}\right)^2},$$

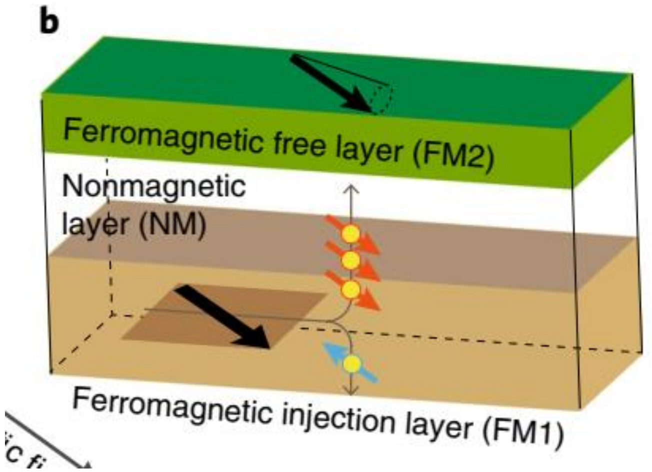
Complete probable angular of spin-torques in (101) plane



Spin-flow direction: $N \times J_C = (N_y \hat{y} + N_z \hat{z}) \times (\cos\phi\, \hat{x} + \cos\phi\, \hat{y}) J_C \propto \hat{z} \cos\phi$

Spin vector: $N \times J_C = N_\parallel \sin\phi\, \widehat{\phi_\parallel} + N_\perp \cos\phi\, \widehat{\phi_\perp} + N_z \hat{z}$

Angular dependence of imparted torque:
Angular dependence of spin current x angular dependence of spin flow direction



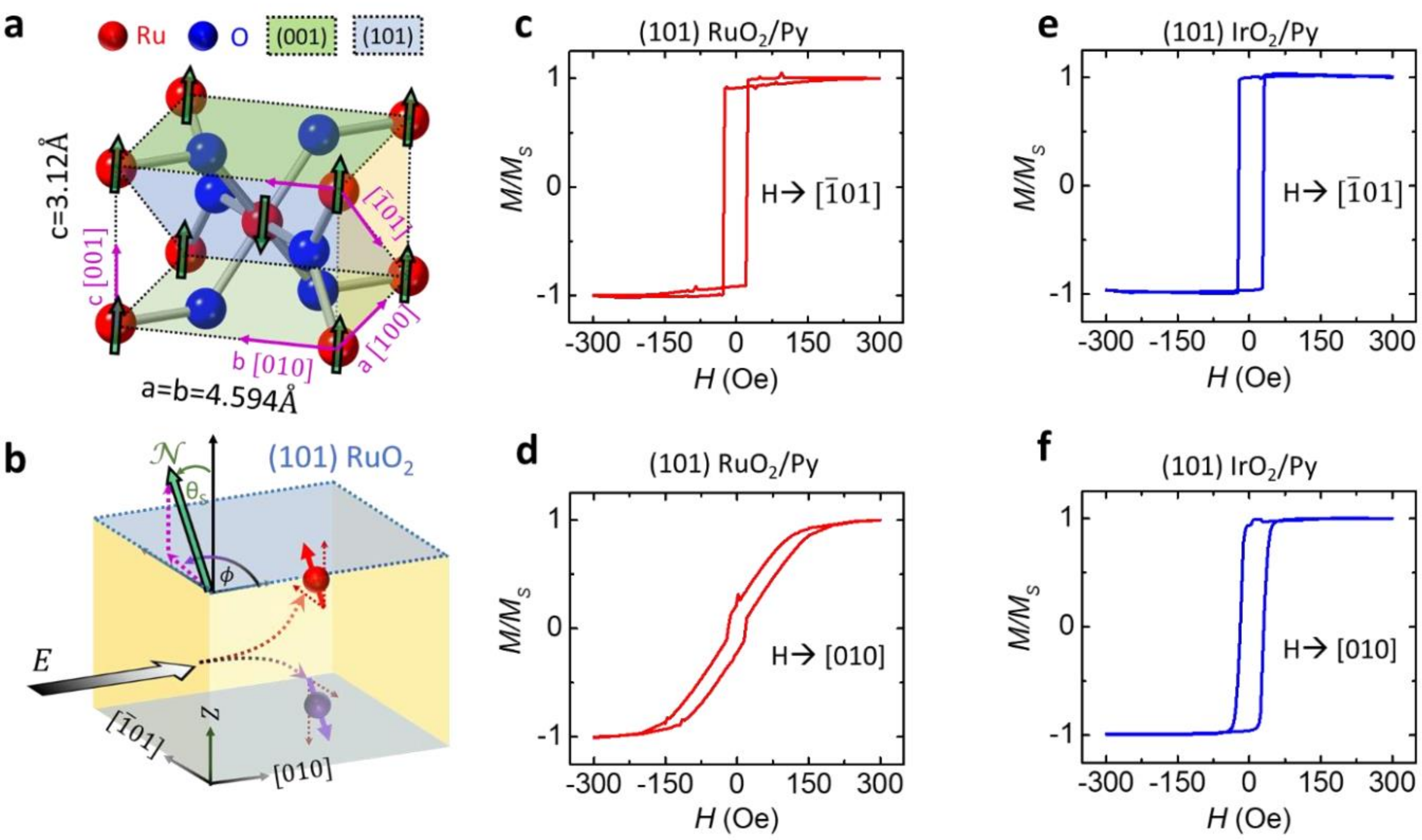
In-plane damping-like torque from m-SHE $\propto \cos^2\phi$

In-plane Dresselhaus-like torque from m-SHE $\propto \sin\phi \cos\phi$

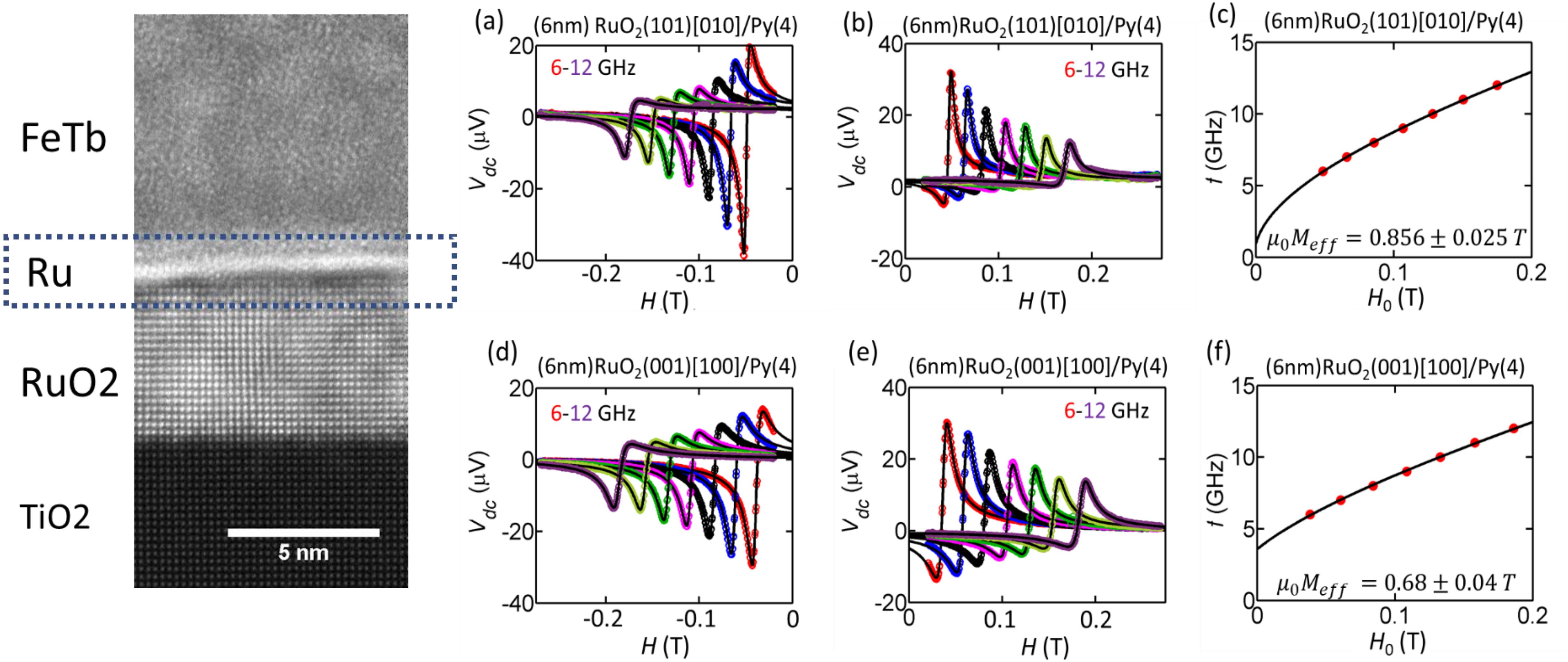
Out-of-plane damping-like torque from m-SHE $\propto \cos\phi$

Satoshi Iihama et. al. Nature Electronics 1, 120 (2021)

Taniguchi, T., Grollier, J. & Stiles, M. D. *Phys. Rev. Applied* **3**, 044001 (2015)



a
Ru
O
(001)
(101)
c=3.12Å
c [001]
b [010]
a [100]
[$\bar{1}$01]
a=b=4.594Å
b
(101) RuO$_2$
$\mathcal{N}$
θ$_s$
ϕ
E
Z
[$\bar{1}$01]
[010]
c
(101) RuO$_2$/Py
H→ [$\bar{1}$01]
d
(101) RuO$_2$/Py
H→ [010]
e
(101) IrO$_2$/Py
H→ [$\bar{1}$01]
f
(101) IrO$_2$/Py
H→ [010]
M/M_S
H (Oe)


FeTb
Ru
RuO2
TiO2
5 nm
(a) (6nm) RuO2(101)[010]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(b) (6nm)RuO2(101)[010]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(c) (6nm)RuO2(101)[010]/Py(4)
f (GHz)
μ0Meff = 0.856 ± 0.025 T
H0 (T)
(d) (6nm)RuO2(001)[100]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(e) (6nm)RuO2(001)[100]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(f) (6nm)RuO2(001)[100]/Py(4)
f (GHz)
μ0Meff = 0.68 ± 0.04 T
H0 (T)

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