Field-Like Torque Sign Reversal in RuO_2/FM Heterostructures with Unsaturated Thickness Dependence

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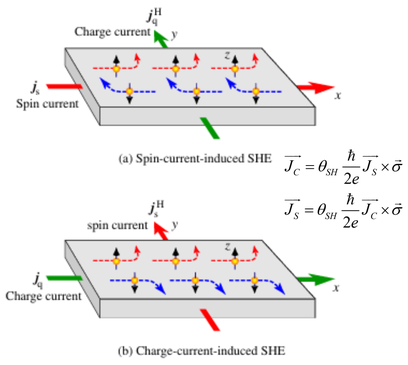
Introduction

➢ Spin Hall Effect

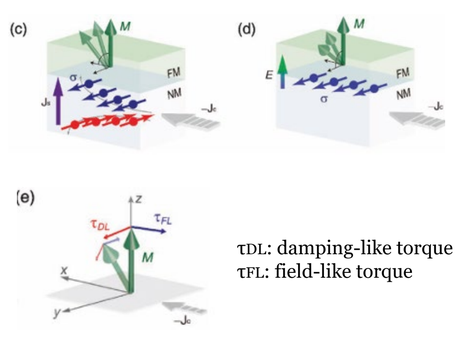


$\vec{J}_C = \theta_{SH}\frac{\hbar}{2e}\vec{J}_S \times \vec{\sigma}$

$\vec{J}_S = \theta_{SH}\frac{\hbar}{2e}\vec{J}_C \times \vec{\sigma}$

Takahashi et al., Adv. Mater. 9, 014105 (2008)

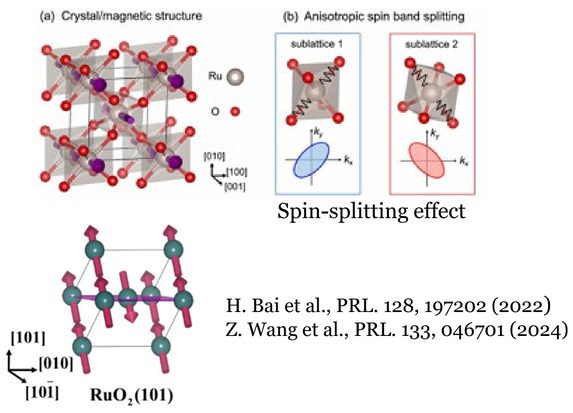
➢ Spin-Orbit Torques



τ_{DL}: damping-like torque
τ_{FL}: field-like torque

J. Ryu et al., Adv. Mater. 32, 1907148 (2020)

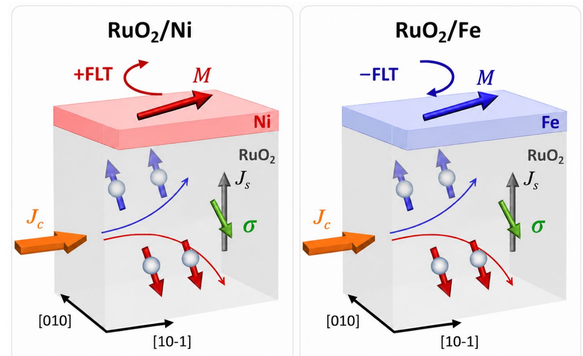
➢ Altermagnet Candidate RuO_2



Spin-splitting effect

H. Bai et al., PRL. 128, 197202 (2022)
Z. Wang et al., PRL. 133, 046701 (2024)

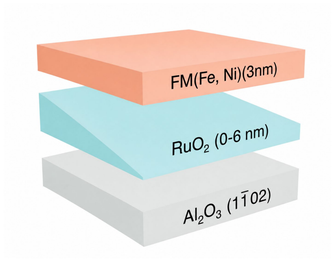
➢ FM-Dependent FLT



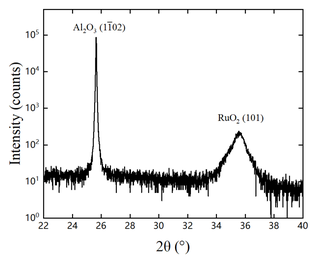
Same RuO_2 spin source, opposite σ_y-induced FLT signs in Ni and Fe.

Sample Preparation

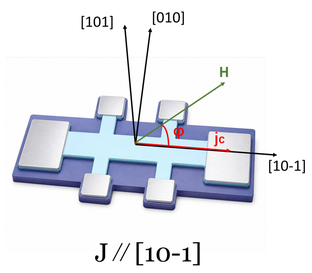
➢ Sample Structure



➢ XRD



➢ SOT Device



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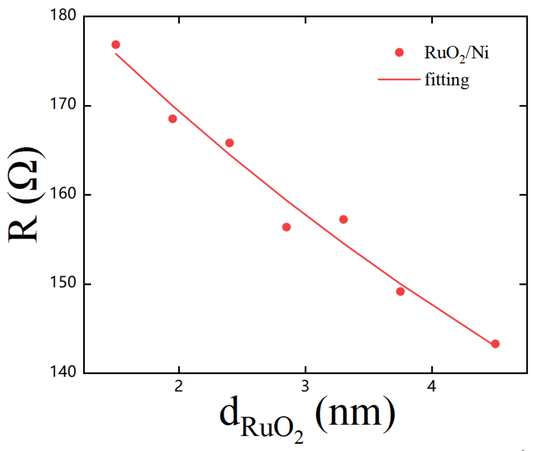
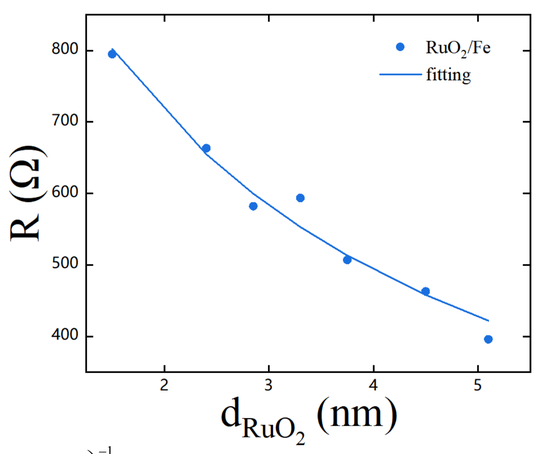
Thickness-dependent measurement on one wedge sample

RuO_2/FM Resistivity Calibration

➢ RuO_2/Ni Resistivity



➢ RuO_2/Fe Resistivity



$$R_{tot} = \frac{L}{w}\left(\frac{d_{RuO}}{\rho_{RuO}} + \frac{d_{FM}}{\rho_{FM}}\right)^{-1}$$

$\rho_{RuO_2} = (7.677 \pm 0.3192)\times 10^{-7}\ \Omega\cdot m$

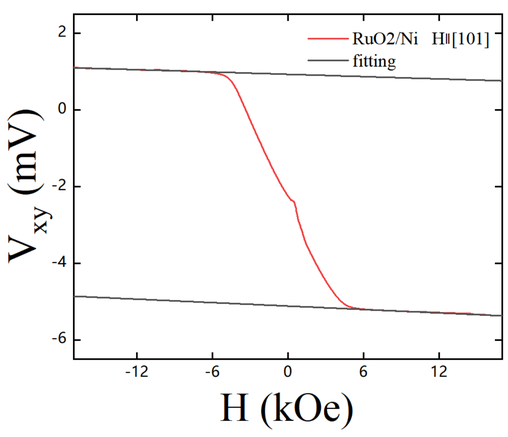
$\rho_{Ni} = (5.004 \pm 0.1231)\times 10^{-7}\ \Omega\cdot m$

$\rho_{RuO_2} = (1.068 \pm 0.0818)\times 10^{-6}\ \Omega\cdot m$

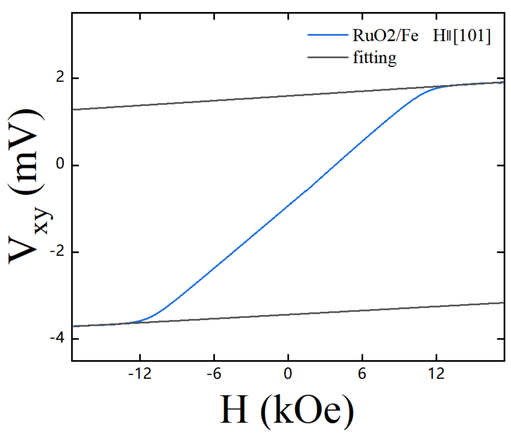
$\rho_{Ni} = (1.285 \pm 0.1044)\times 10^{-6}\ \Omega\cdot m$

Anomalous Hall Voltage Measurement

➢ RuO_2/Ni



➢ RuO_2/Fe



$$V_{xy}(H) = V_{AHE}m_z + V_{OHE}H$$

$$m_z = \frac{M_z}{M_s} = \begin{cases} +1, & \text{positive saturation} \\ -1, & \text{negative saturation} \end{cases}$$

$$V_{AHE} = \frac{V_{xy}(M_z = +M_s) - V_{xy}(M_z = -M_s)}{2}$$

$H_k = 0.54$ T

$V_{AHE} = -2.96\times 10^{-3}$ V

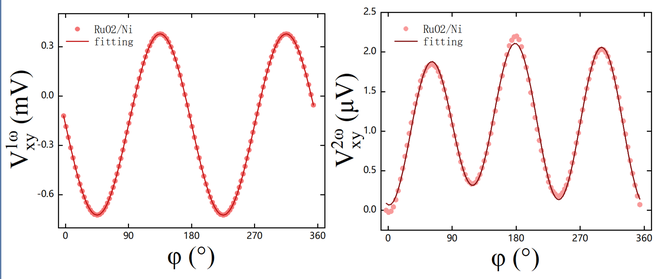
$H_k = 1.12$ T

$V_{AHE} = 2.51\times 10^{-3}$ V

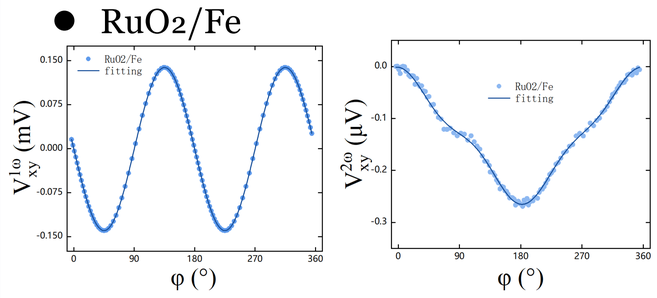
Harmonic Hall Voltage Measurement

➢ First-harmonic voltage & Second-harmonic voltage

- RuO_2/Ni



- RuO_2/Fe

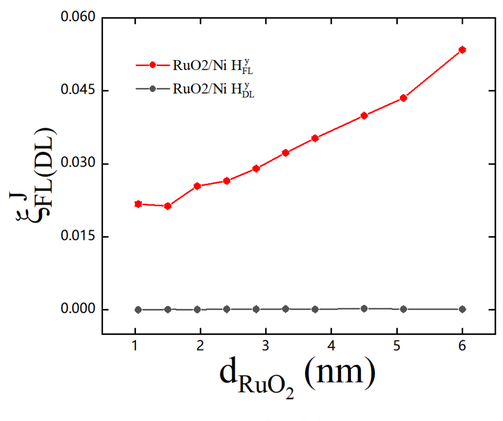


$$V_{1\omega} = V_{PHE}\sin 2\varphi$$

$$V_{2\omega} = V_{\mathrm{PHE}}\frac{H_{\mathrm{FL}}^{y} + H_{Oe}}{H_{\mathrm{ext}}}\cos 2\varphi\cos\varphi + \left(\frac{1}{2}V_{\mathrm{AHE}}\frac{H_{\mathrm{DL}}^{y}}{H_{\mathrm{ext}} + H_k} + V_{ANE}\right)\cos\varphi + V_{\mathrm{PHE}}\frac{H_{\mathrm{FL}}^{x}}{H_{\mathrm{ext}}}\cos 2\varphi\sin\varphi + \frac{1}{2}V_{\mathrm{AHE}}\frac{H_{\mathrm{DL}}^{x}}{H_{\mathrm{ext}} + H_k}\sin\varphi + V_{\mathrm{PHE}}\frac{H_{\mathrm{DL}}^{z}}{H_{\mathrm{ext}}}\cos 2\varphi + \frac{1}{2}V_{\mathrm{AHE}}\frac{H_{\mathrm{FL}}^{z}}{H_{\mathrm{ext}} + H_k} + V_{PNE}\sin 2\varphi + C$$

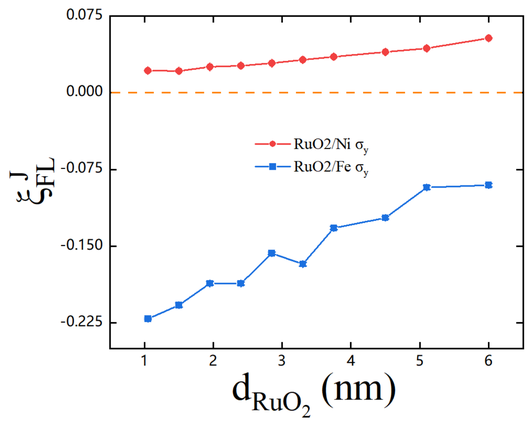
Extraction of SOT effective fields from harmonic hall fitting

Thickness Dependence of SOT Efficiency



$$\xi_{DL(FL)} = \frac{2e}{\hbar}\frac{M_s t_{FM}}{J_{NM}}H_{DL(FL)}$$

$\xi_{FL} \gg \xi_{DL}$



Opposite FLT in RuO_2/Ni and RuO_2/Fe

Summary

- Field-like torque dominates the SOT response in RuO_2/FM heterostructures.
- The σ_y-induced field-like torque reverses sign between RuO_2/Ni and RuO_2/Fe.
- The SOT efficiency remains unsaturated up to 6 nm RuO_2, suggesting possible long-range spin/orbital transport.
- The origin of the FLT sign reversal and thickness dependence requires further investigation.

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