# Spin-Orbit Torque on Magnetic Two-Dimensional Materials


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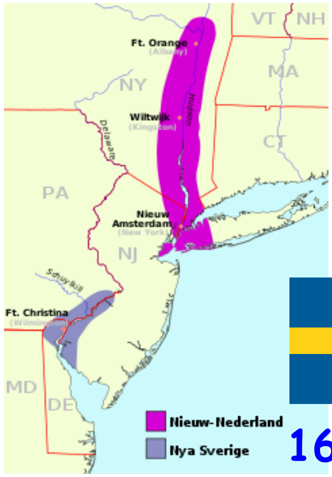
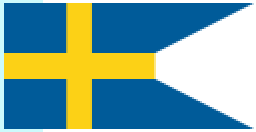
https://wiki.physics.udel.edu/qttg

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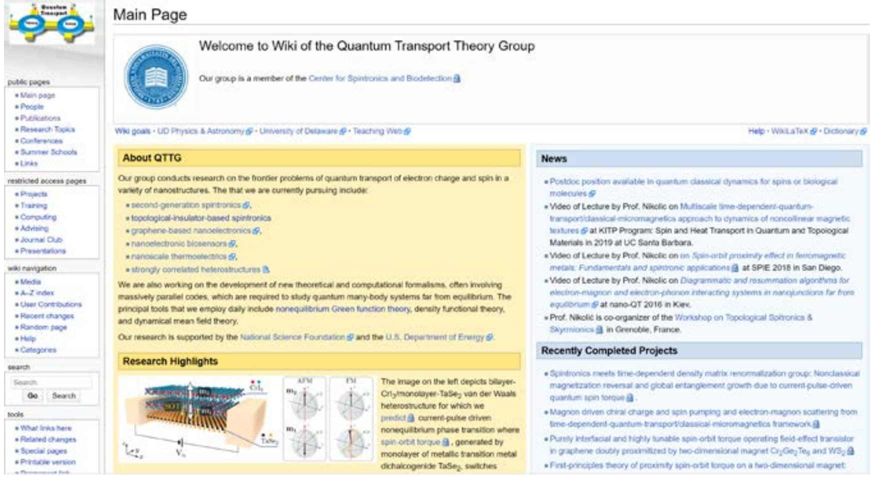
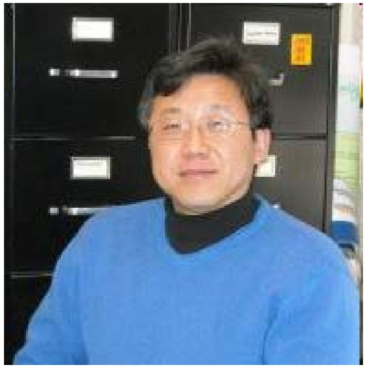


# Collaborators

## Experiment



Prof. J. Q. Xiao

## Theory & Computation

Dr. Kapildeb Dolui

Dr. Marko D. Petrović

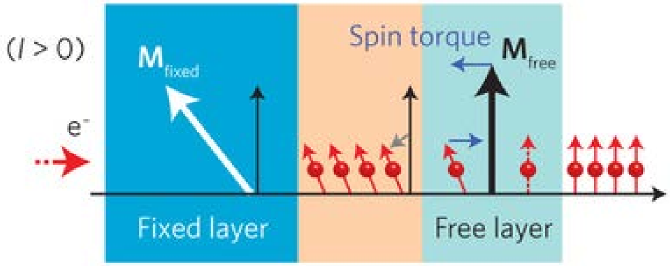
Klaus Zollner

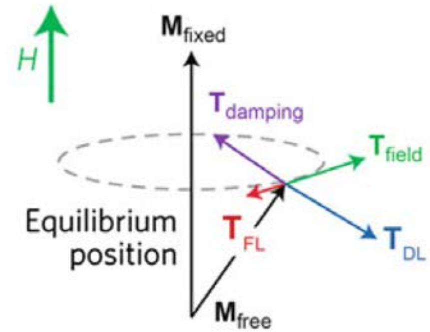
Prof. Jaroslav Fabian

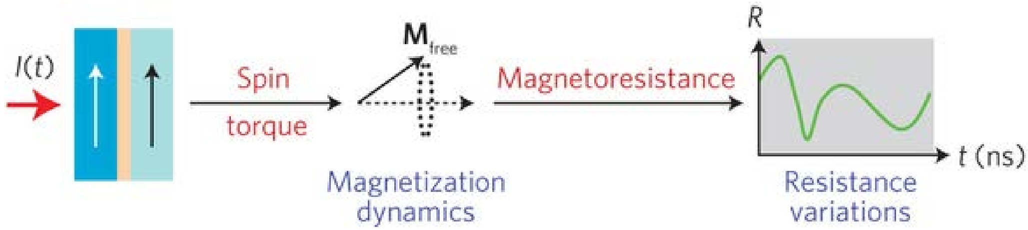
Prof. Petr Plecháč

# Spin-Transfer Torque (STT): Fundamentals and Applications

Fundamentals



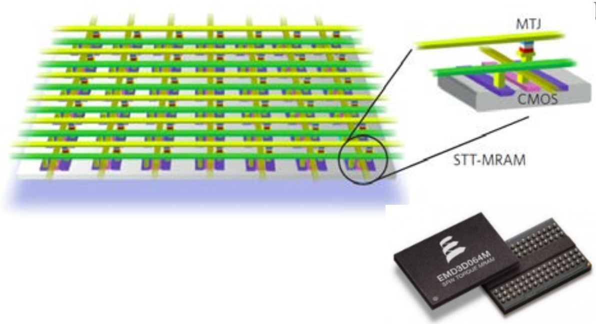




$$\mathbf{T} \;\propto\; \sum_i \langle \hat{\mathbf{s}}_i \rangle \times \mathbf{M}_{\mathrm{free}} = \mathbf{T}_{\mathrm{DL}} + \mathbf{T}_{\mathrm{FL}}$$

$$\langle \hat{\mathbf{s}}_i \rangle \;=\; \mathrm{Tr}_{\mathrm{spin}}\left[\hat{\rho}_{\mathrm{neq}} \hat{\boldsymbol{\sigma}}\right]$$

Applications

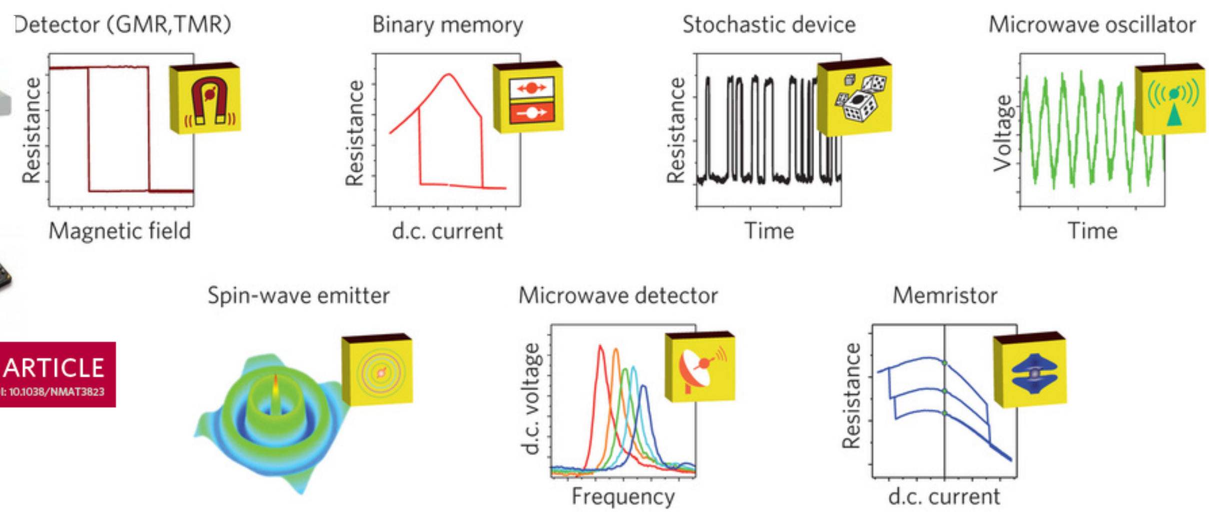



nature materials | PROGRESS ARTICLE

PUBLISHED ONLINE: 17 DECEMBER 2013 | DOI: 10.1038/NMAT3823

**Spin-torque building blocks**

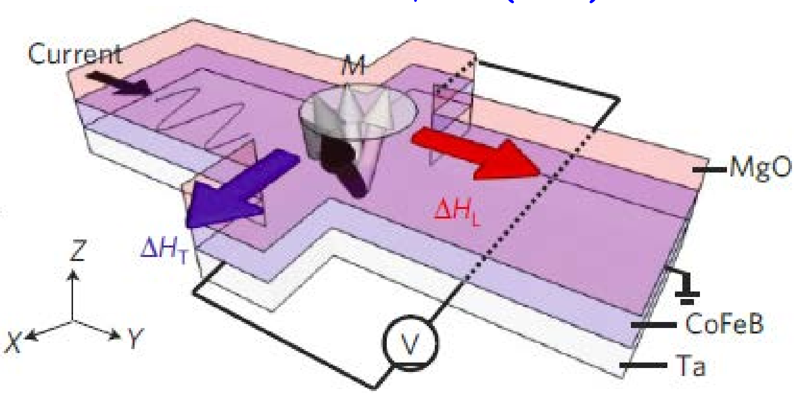
N. Locatelli, V. Cros and J. Grollier*



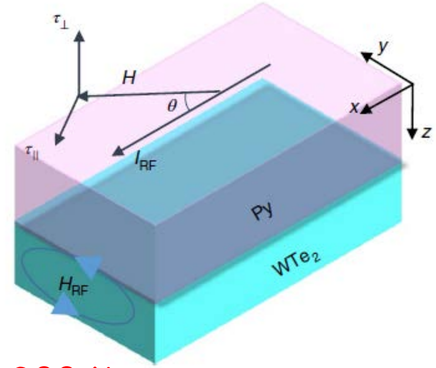
# Spin-Orbit Torque (SOT): Fundamentals and Applications

Fundamentals

Nat. Mater. **12**, 240 (2013)

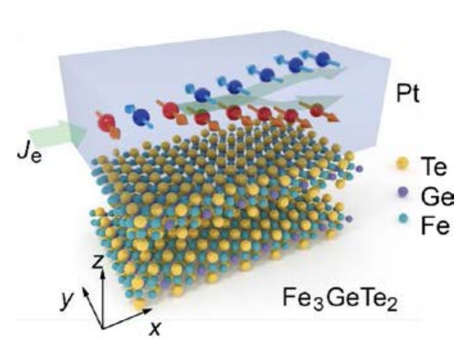



Nat. Nanotech. **14**, 945 (2019)




T=300 K
Magnetization switching with ultralow current density ~$3\times10^5$ A/cm$^2$

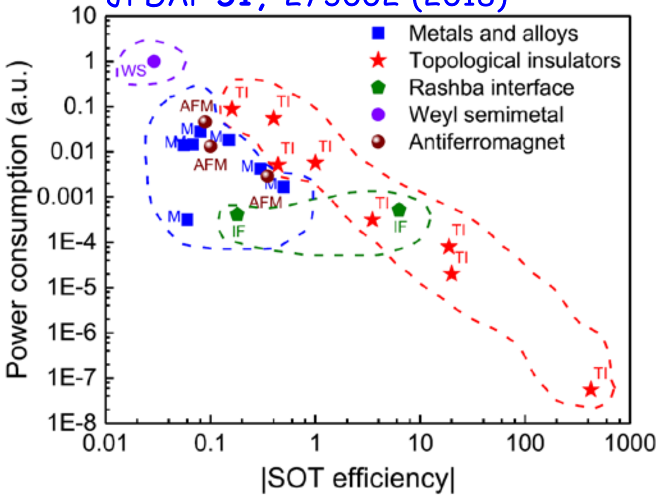
Nano Lett. **19**, 4400 (2019)
Sci. Adv. **5**, eaaw8904 (2019)




T~225 K
Switching with current density ~$3\times10^7$ A/cm$^2$
**but gate tunable**

Applications

JPDAP **51**, 273002 (2018)



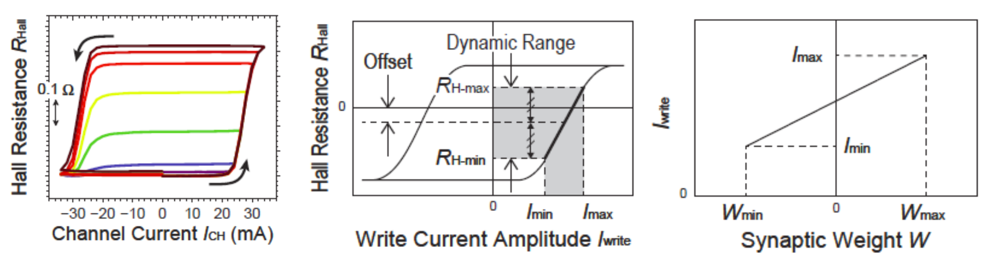

high efficiency of SOT-driven magnetization switching demonstrated: 60 fJ (vs. 150 fJ to 4 pJ with STT) energy consumed per bit writing

solid-state nonvolatile analogue memory with infinite read-write endurance

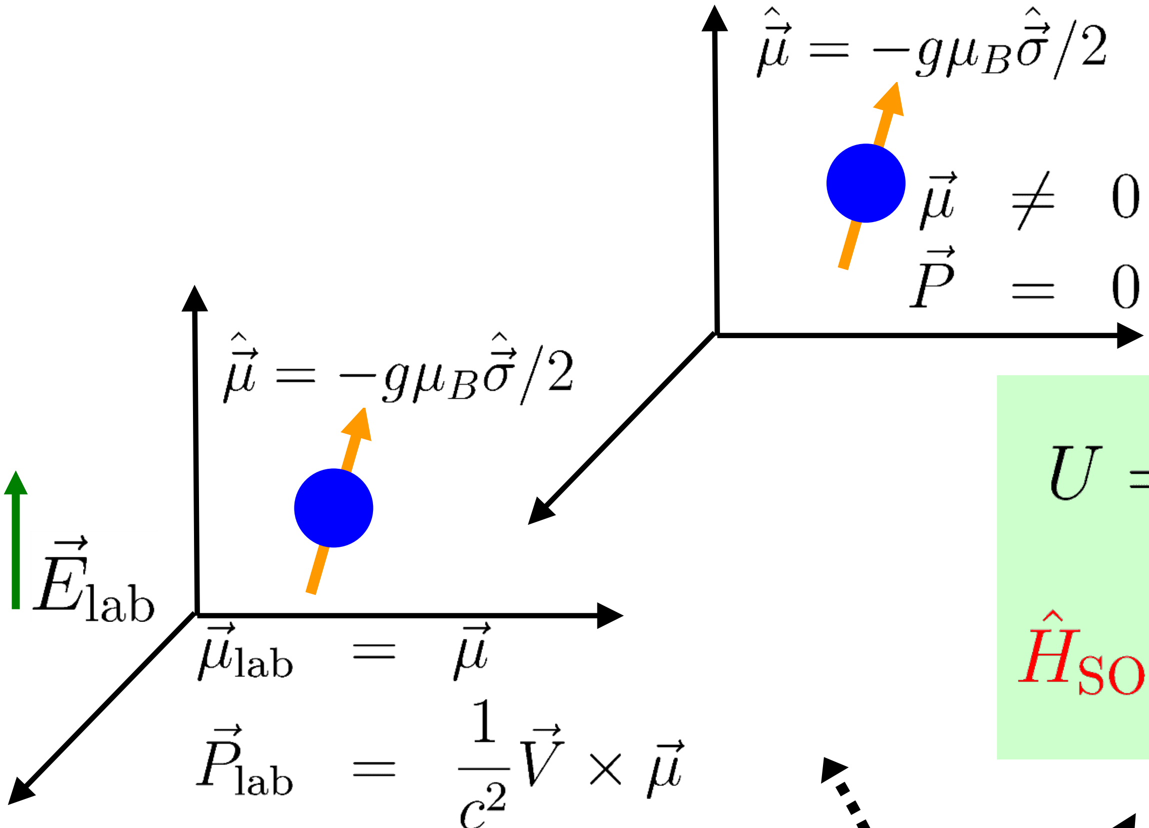

Applied Physics Express **10**, 013007 (2017)
https://doi.org/10.7567/APEX.10.013007


**Analogue spin–orbit torque device for artificial-neural-network-based associative memory operation**


William A. Borders[1], Hisanao Akima[1*], Shunsuke Fukami[1,2,3,4*], Satoshi Moriya[1], Shouta Kurihara[1], Yoshihiko Horio[1], Shigeo Sato[1], and Hideo Ohno[1,2,3,4,5]

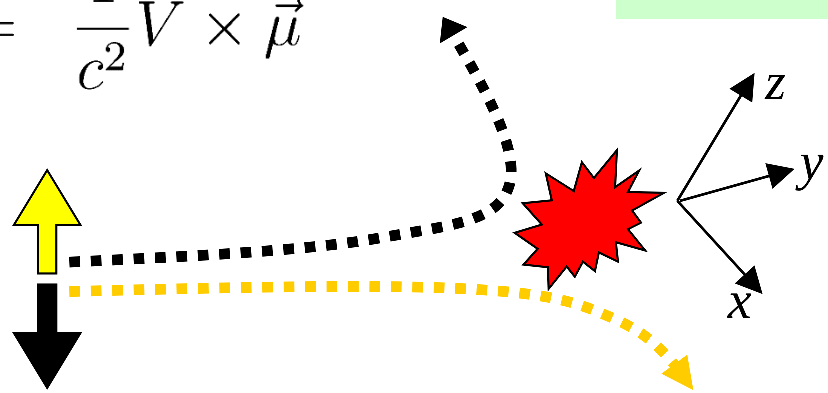



# Crash Course on Spin-Orbit Coupling (SOC)




$$U = -\frac{1}{2}\vec{P}_{\mathrm{lab}} \cdot \vec{E}$$

$$\hat{H}_{\mathrm{SO}} = \frac{e\hbar^2}{4m_0^2c^2}(\hat{\vec{\sigma}} \times \hat{\vec{p}}) \cdot \vec{E}$$




SO deflection force:

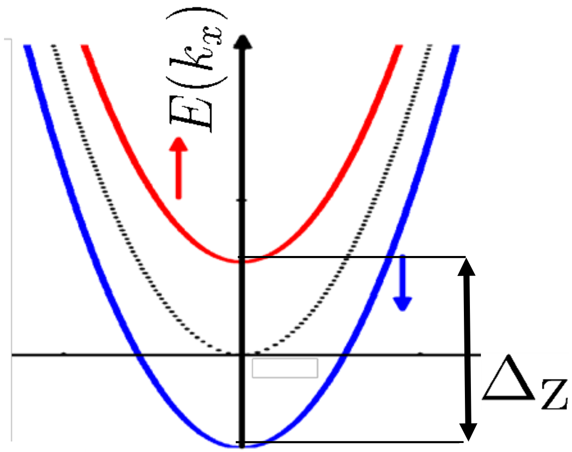
$$F_{\mathrm{SO}} = \pm P_{\mathrm{lab}} \nabla E_x$$

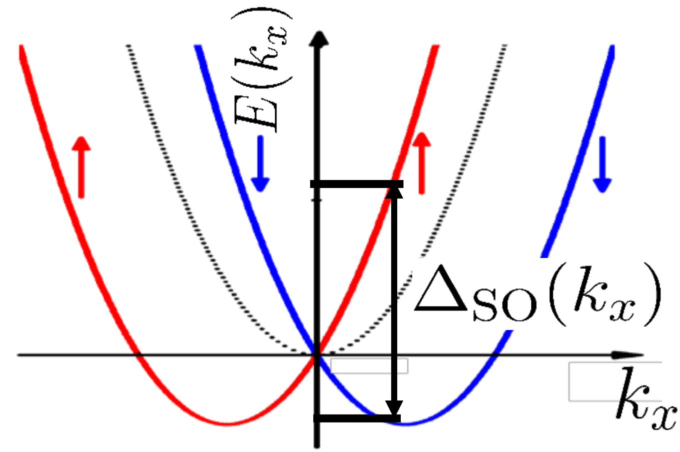
# Crash Course on Rashba SOC

$$\hat{H}_{\rm SO}^{\rm R} = \frac{\alpha}{\hbar}(\hat{\boldsymbol{\sigma}} \times \hat{\mathbf{p}}) \cdot \mathbf{e}_z \equiv -\frac{g\mu_B}{2}\hat{\boldsymbol{\sigma}} \cdot \mathbf{B}_{\rm R}(\hat{\mathbf{p}})$$

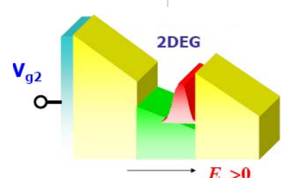
**1D:**

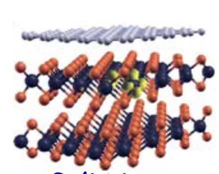
$E(k_x)$

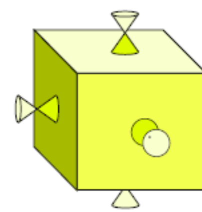



**2D:**



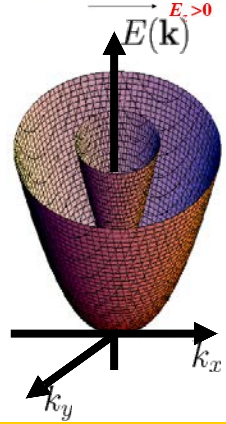





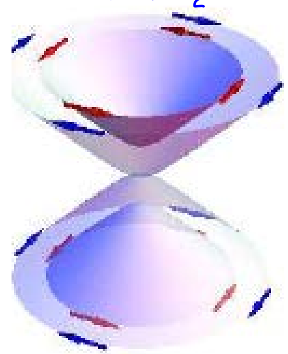
$$\varepsilon(\mathbf{k},\uparrow) = \varepsilon(-\mathbf{k},\downarrow)$$

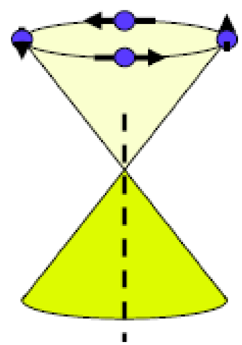
$$\varepsilon(\mathbf{k},\uparrow) \neq \varepsilon(-\mathbf{k},\uparrow)$$

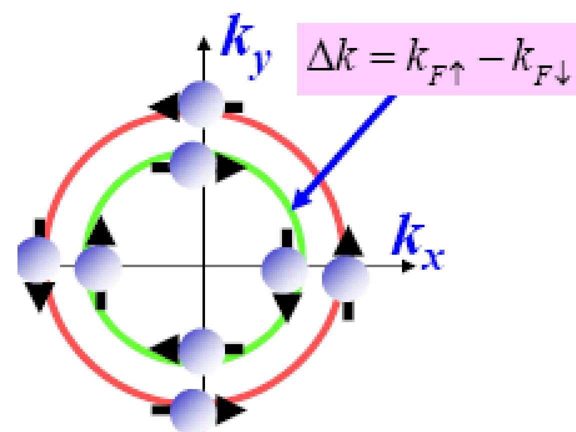
$$\varepsilon(\mathbf{k},\uparrow) \neq \varepsilon(\mathbf{k},\downarrow)$$




G/WS$_2$

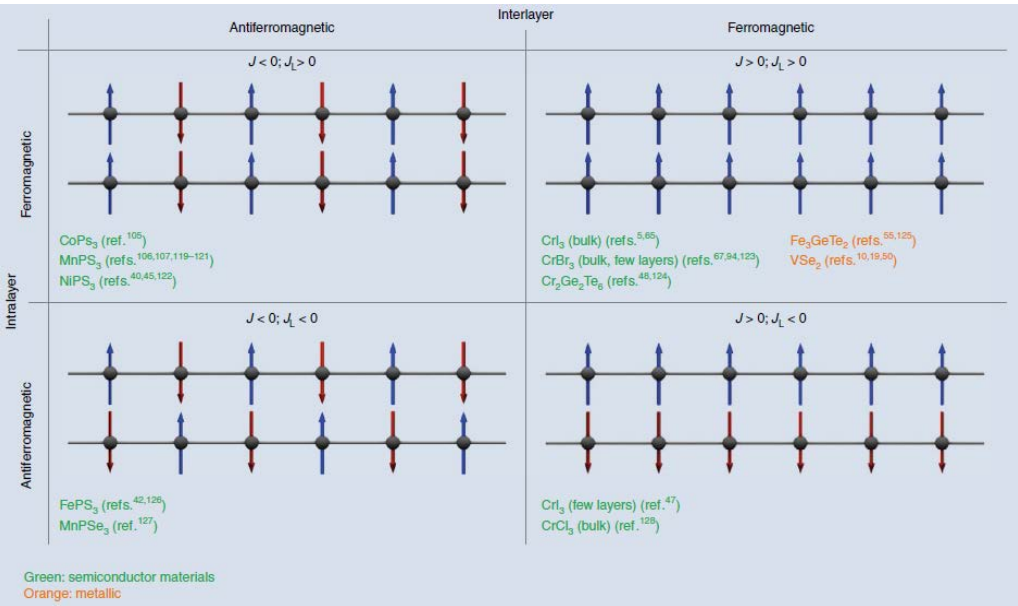


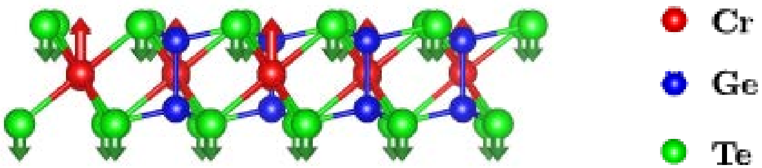


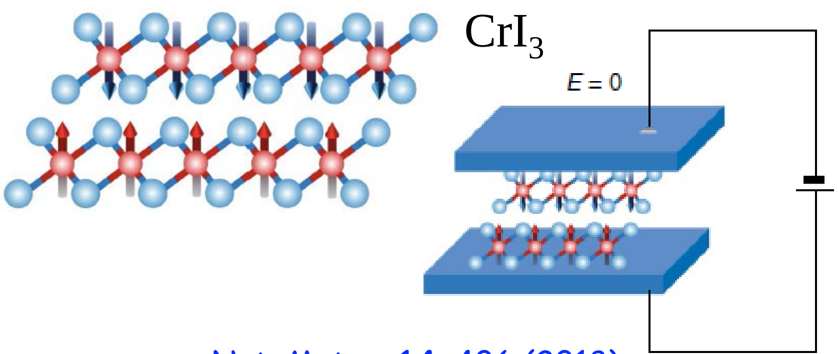


# Crash Course on Two-Dimensional Magnets Derived from Layered vdW Materials

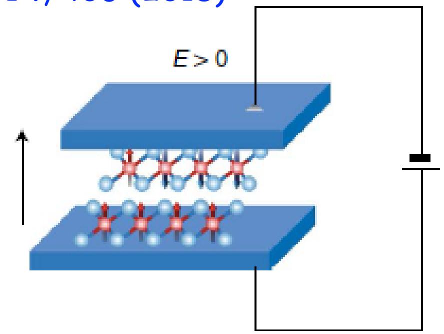
Nat. Nanotech. **14**, 408 (2019)

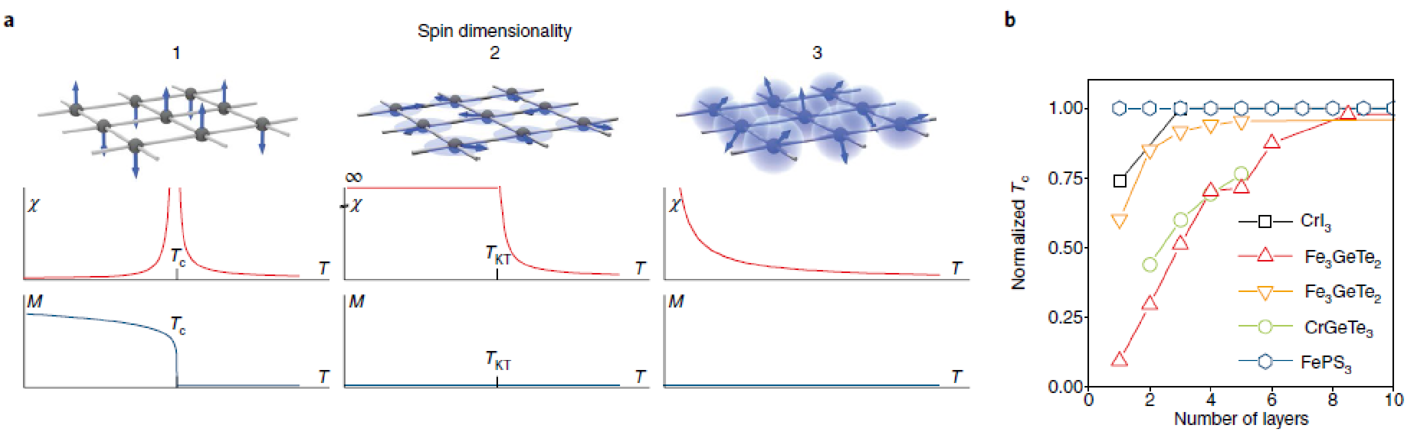


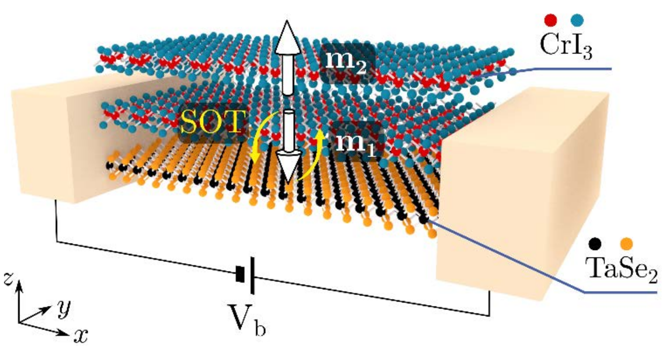

Nat. Mater. **14**, 406 (2018)

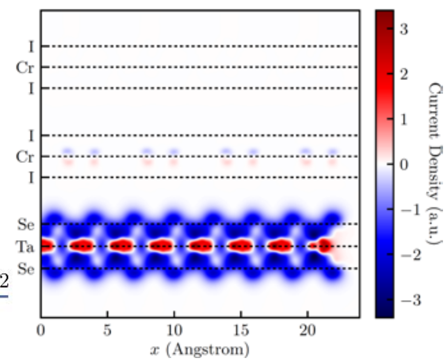


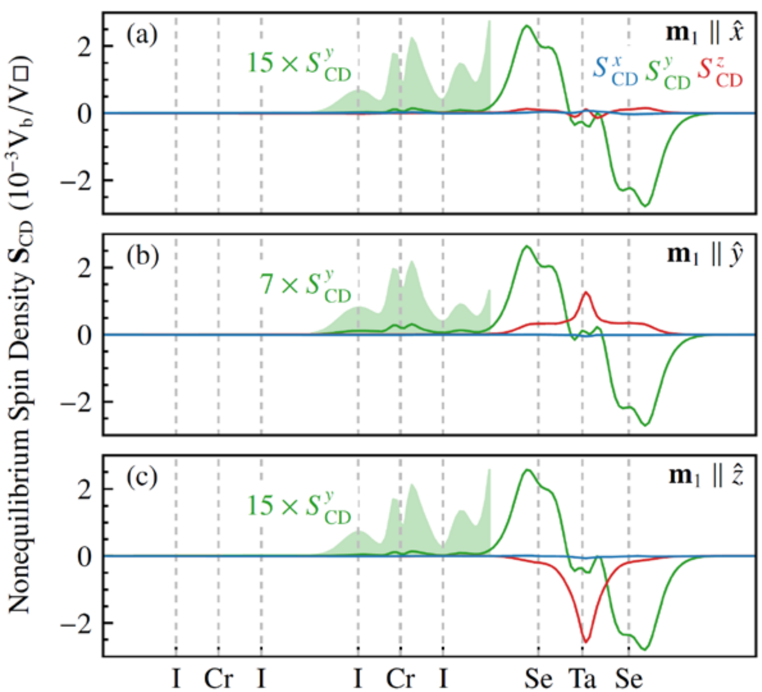



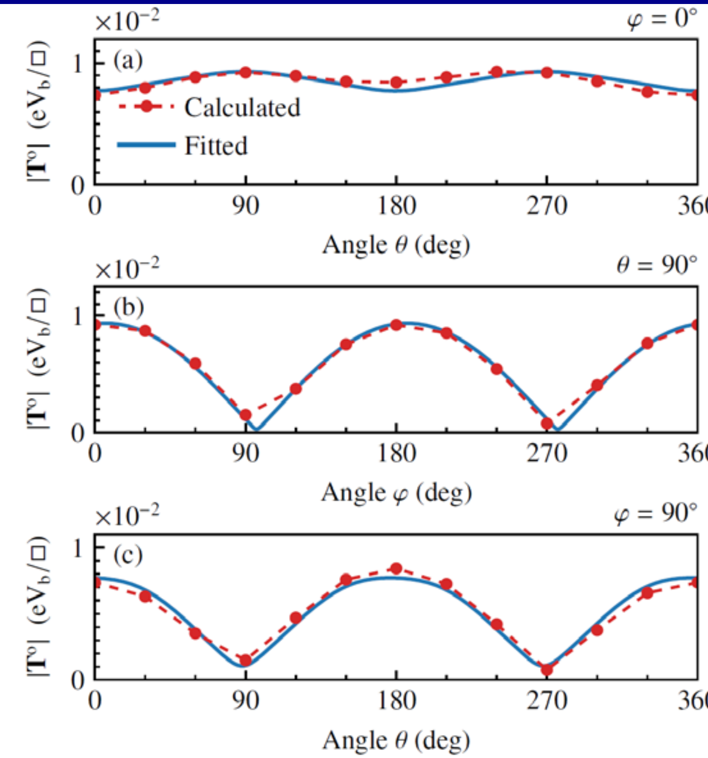
# SOT in bilayer-$CrI_3$/monolayer-$TaSe_2$ vdW Heterostructure

Nano Lett. https://doi.org/10.1021/acs.nanolett.9b04556 (2020)



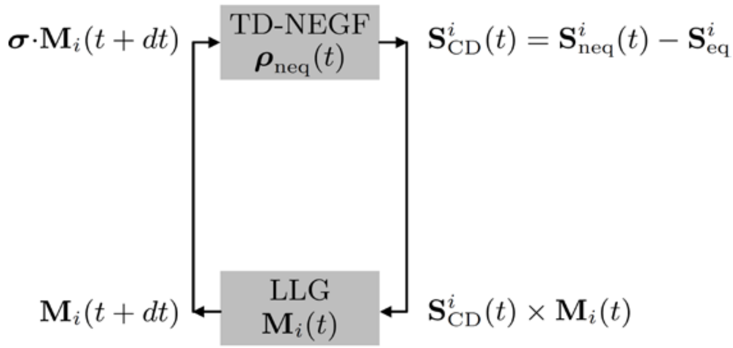




$$\mathbf{T}^{\mathrm{o}} = (\mathbf{p}\times\mathbf{m}_1)\left[\sum_{n=0}^{\infty}\tau^{\mathrm{o}}_{n\alpha}|\hat{z}\times\mathbf{m}_1|^{2n}\right] + \mathbf{m}_1\times(\hat{z}\times\mathbf{m}_1)(\mathbf{m}_1\cdot\hat{x})\left[\sum_{n=0}^{\infty}\tau^{\mathrm{o}}_{n\beta}|\hat{z}\times\mathbf{m}_1|^{2n}\right]$$

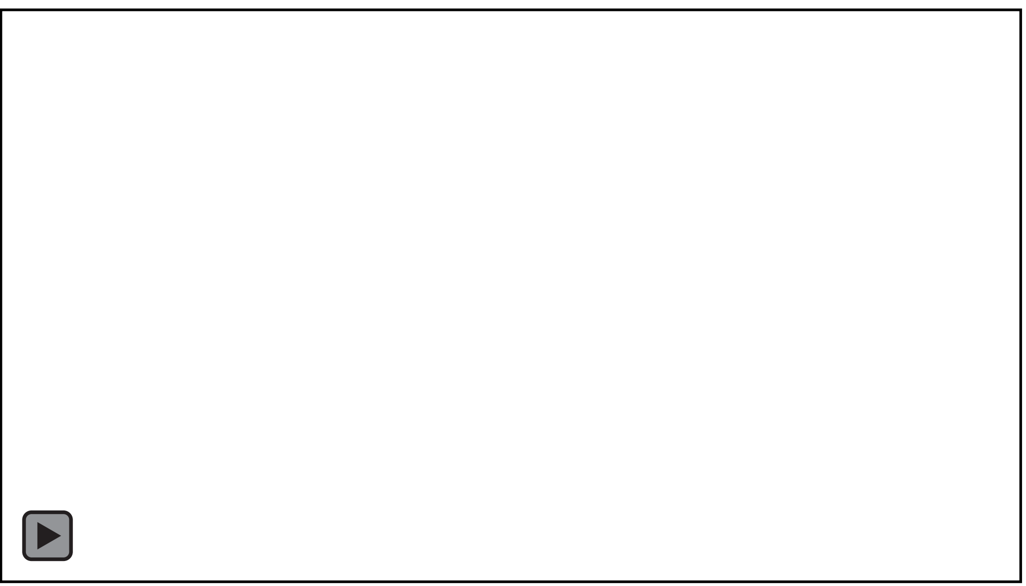
| $\mathbf{p}(\theta,\phi)$ | $\tau^{\mathrm{o}}_{0\alpha}$ | $\tau^{\mathrm{o}}_{1\alpha}$ | $\tau^{\mathrm{o}}_{2\alpha}$ | $\tau^{\mathrm{o}}_{3\alpha}$ | $\tau^{\mathrm{o}}_{0\beta}$ | $\tau^{\mathrm{o}}_{1\beta}$ |
|---|---|---|---|---|---|---|
| (88°, 98°) | 77.22 | 17.32 | -30.32 | 13.54 | -9.19 | -6.88 |

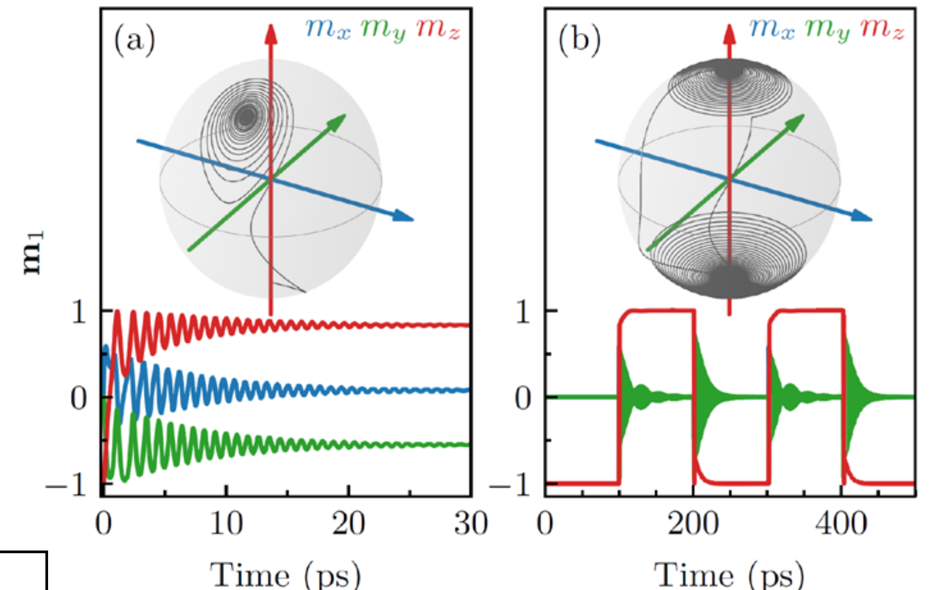
# SOT Driven AFM-FM Nonequilibrium Phase Transition in bilayer-$CrI_3$/monolayer-$TaSe_2$

PRApplied **10**, 054038 (2018)

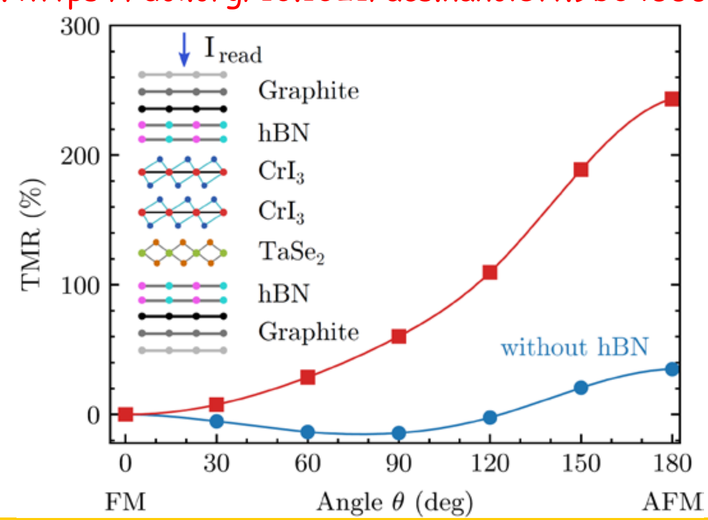



$$\frac{d\mathbf{m}_1}{dt} = -\gamma \mathbf{m}_1 \times \mathbf{B}_1^{\rm eff} + \lambda \mathbf{m}_1 \times \frac{d\mathbf{m}_1}{dt} + \frac{\gamma}{\mu_M}\mathbf{T}^{\rm o}$$






Lett. https://doi.org/10.1021/acs.nanolett.9b04556 (2020)



# Conclusions in Pictures

Nano Lett. https://doi.org/10.1021/acs.nanolett.9b04556 (2020)