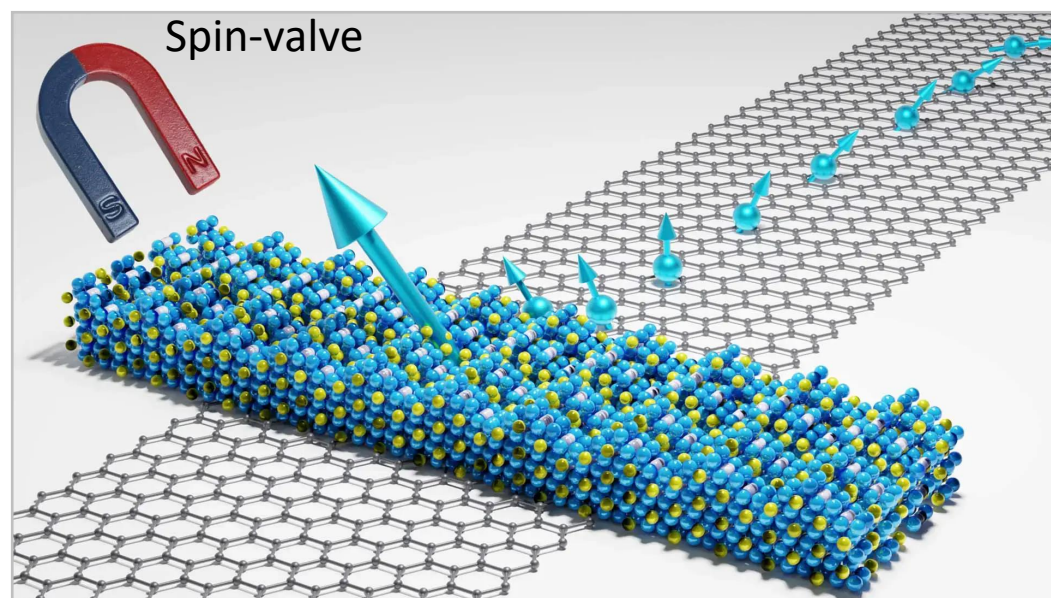
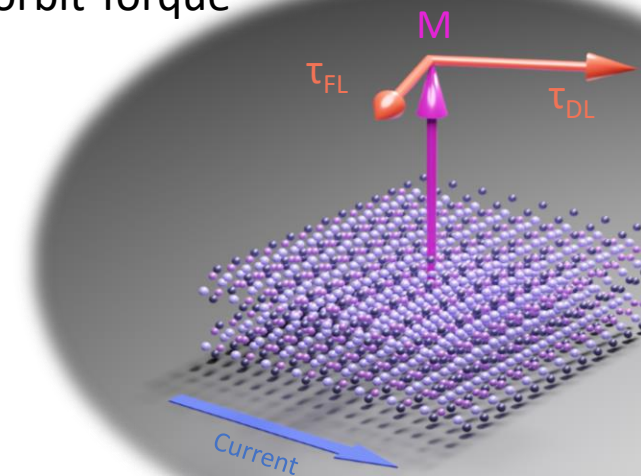


Van der Waals Magnets for Spintronic Devices



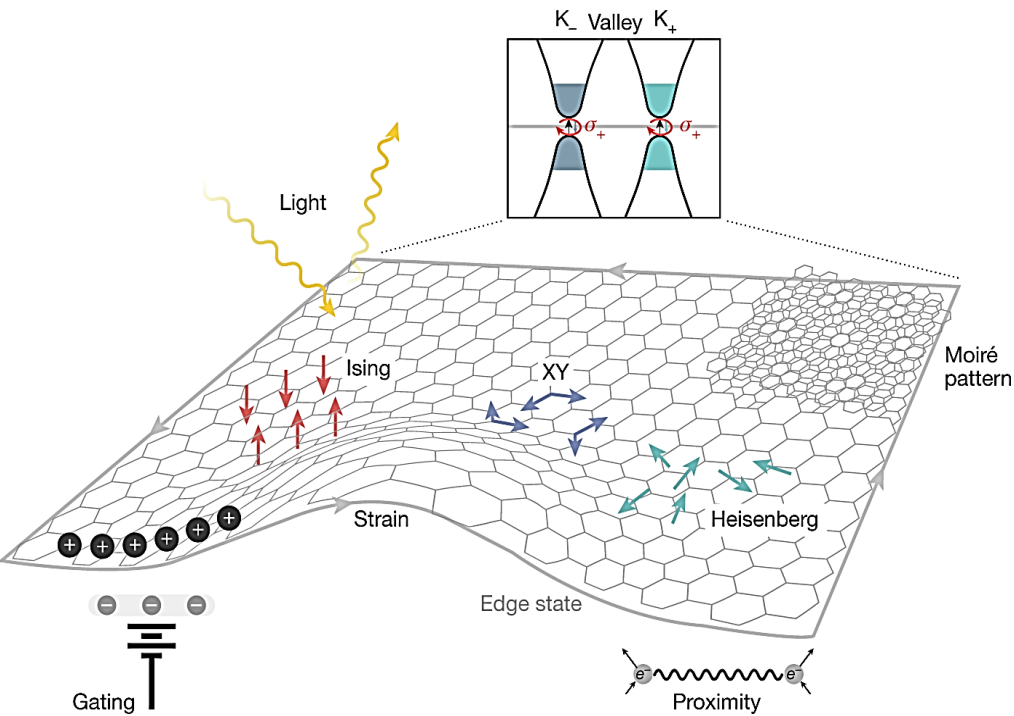
Spin-orbit Torque



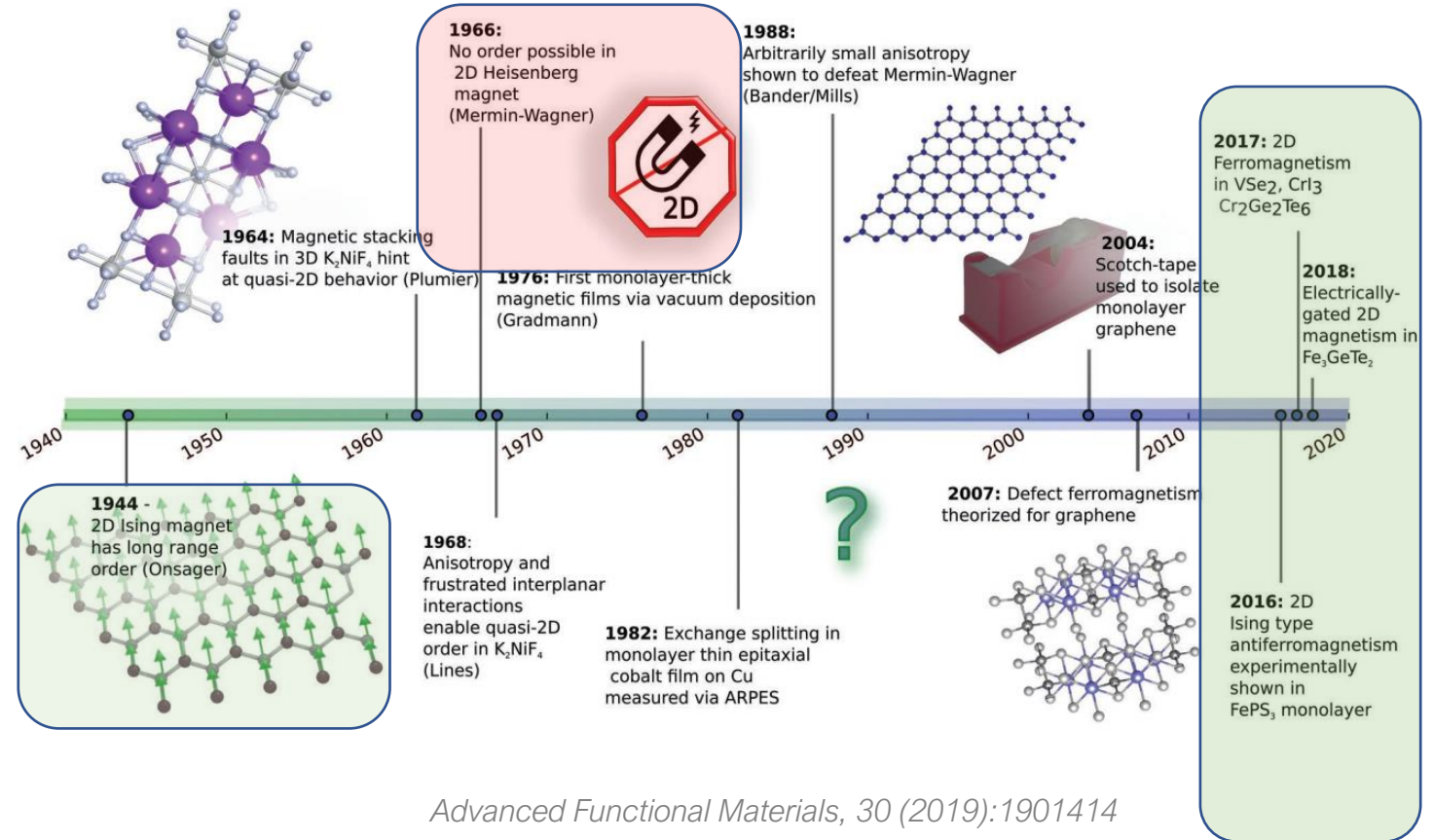
Bing Zhao

Chalmers University of Technology
Sweden

2D Magnet playground

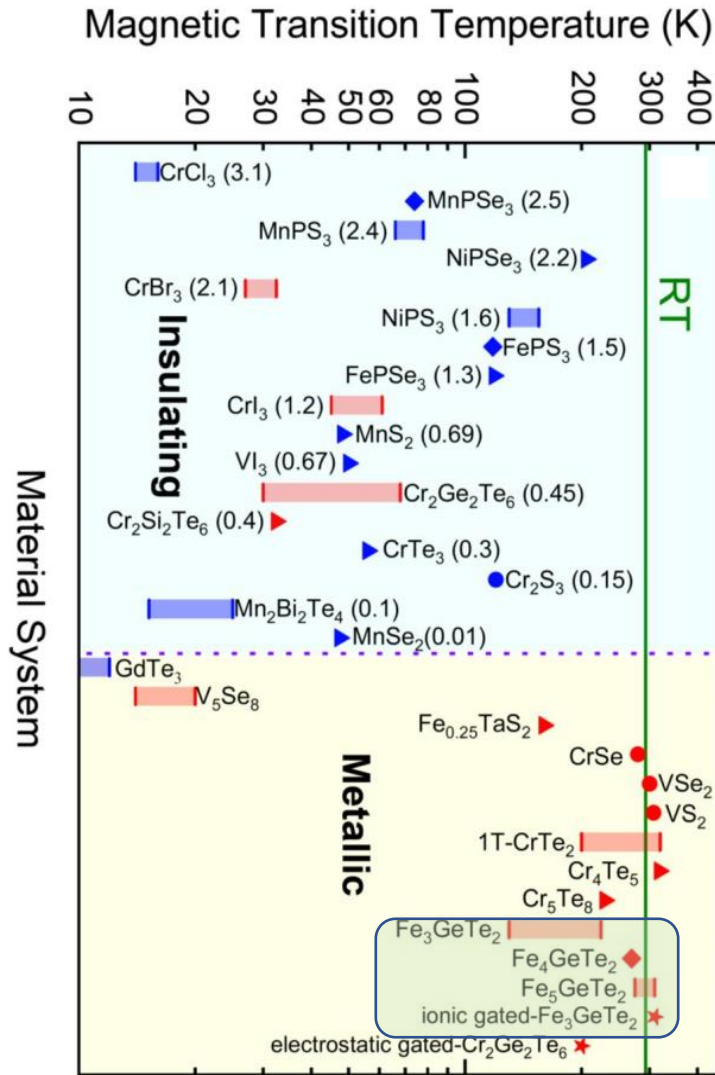


Nature 563.7729 (2018): 47-52.

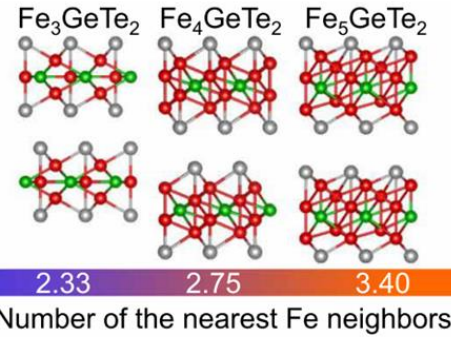


Advanced Functional Materials, 30 (2019):1901414

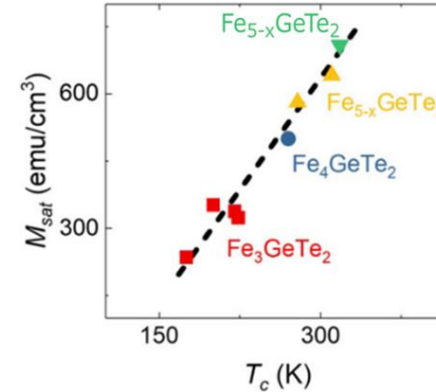
Room temperature vdW Magnet



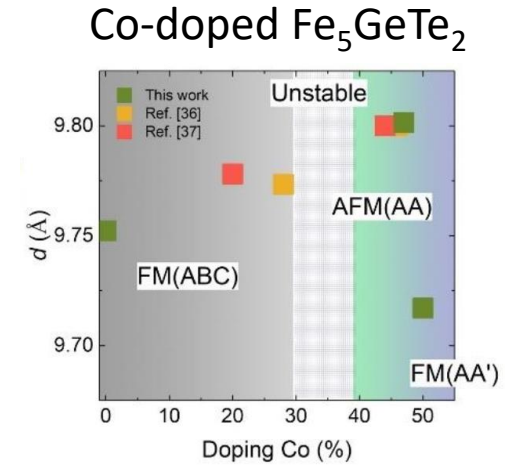
Nature Reviews Physics (2022): 1-17.



Science Advances 6 (2020): eaay8912

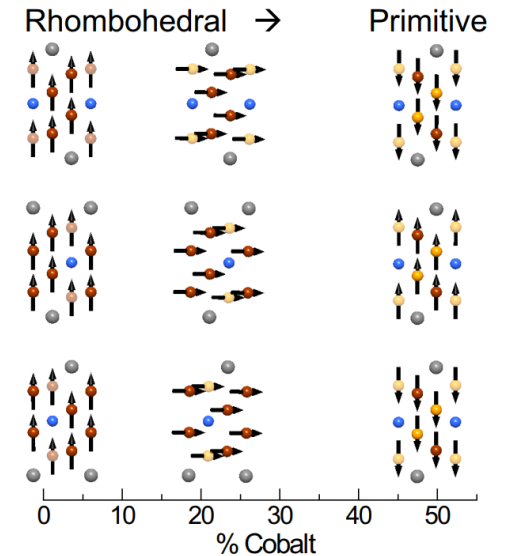


PRB 102 (2020): 064417



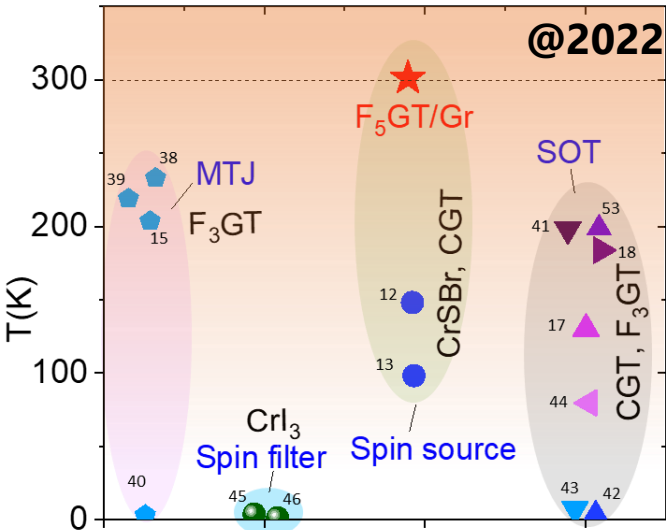
Physical Review Materials 6 (2022): 044403

- ✓ High Curie Temperature
- ✓ Higher saturation M
- ✓ Metallic—electrical control
- ✓ High tunable magnetic properties (MA, Tc, FM/AFM...)



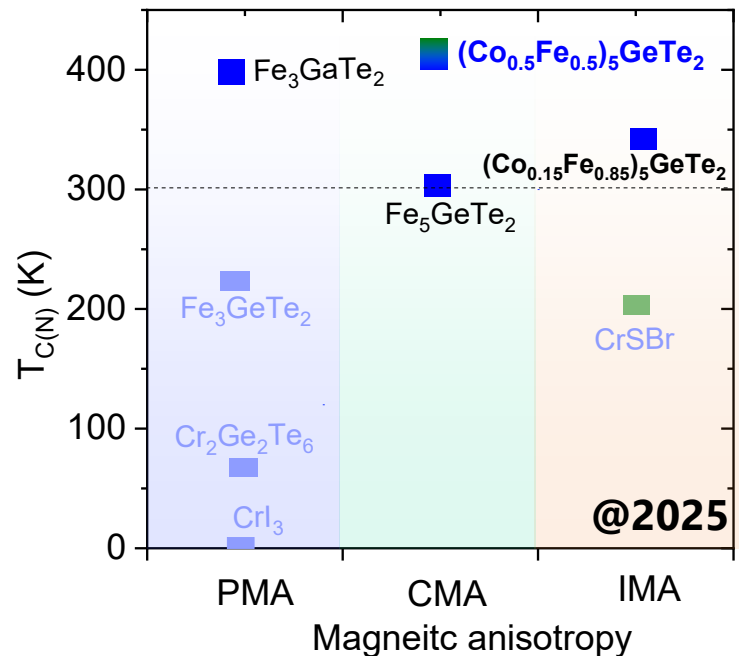
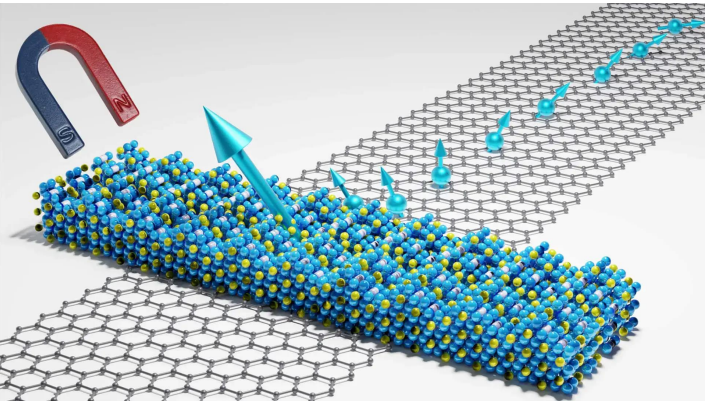
Physical Review Materials 4 (2020): 074008

vdW magnet-based devices

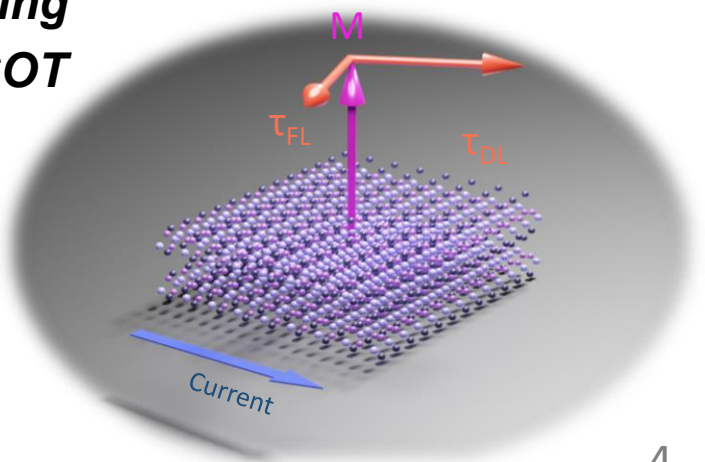


Outline

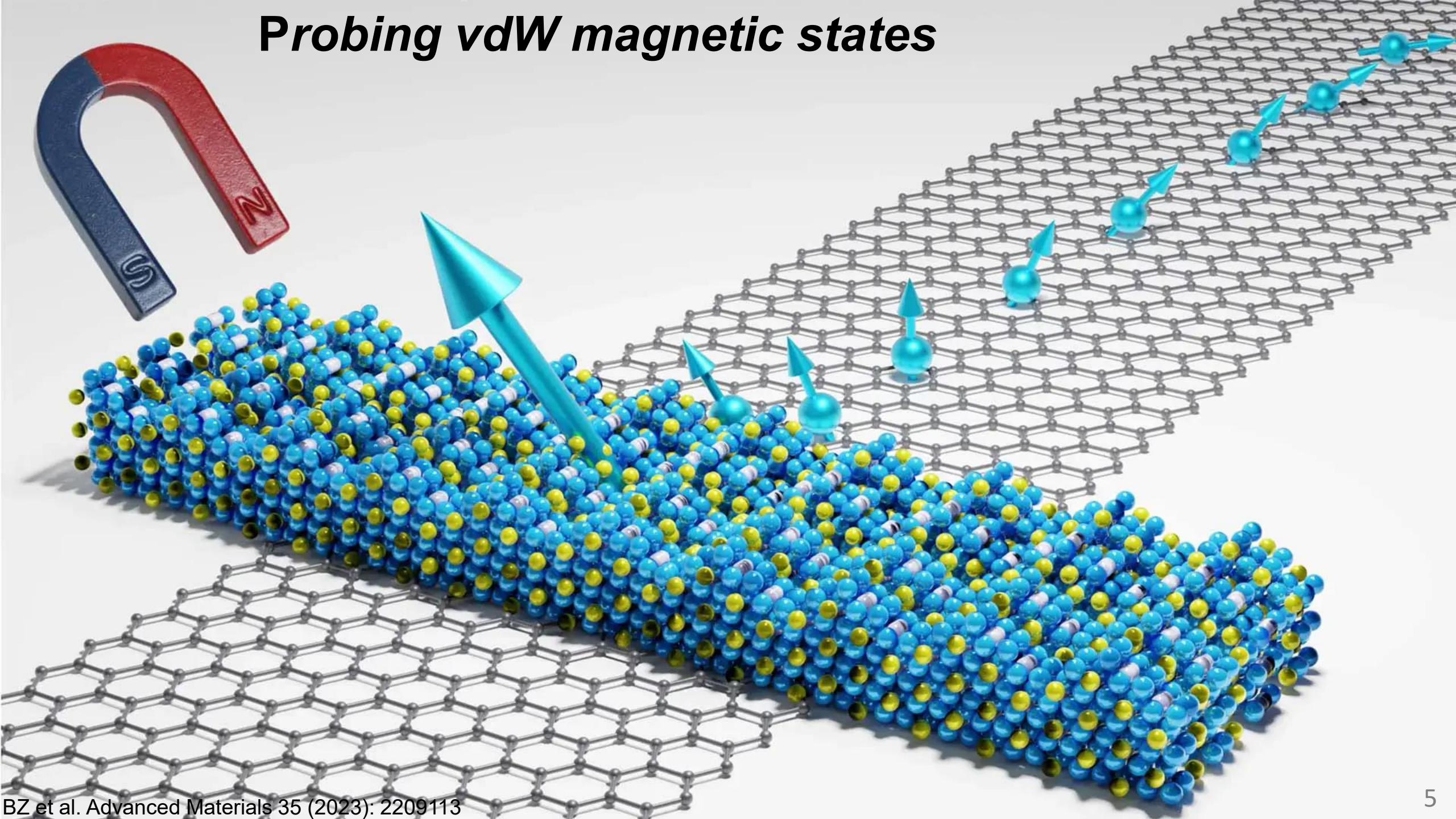
- **Probing vdW magnetic states**
 - ✓ vdW magnets for spin source
 - ✓ *Detecting spin textures*



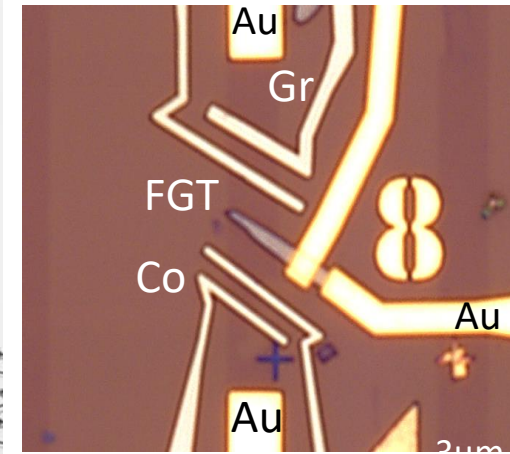
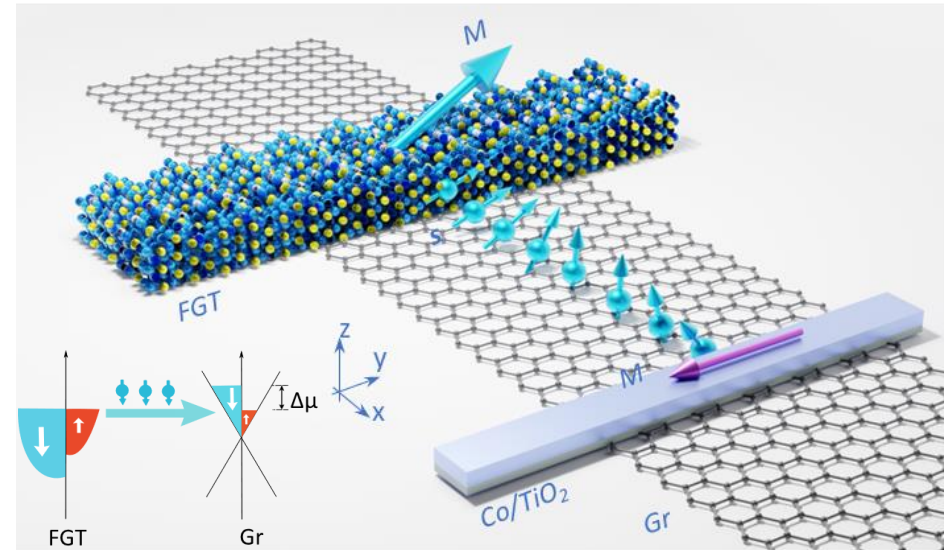
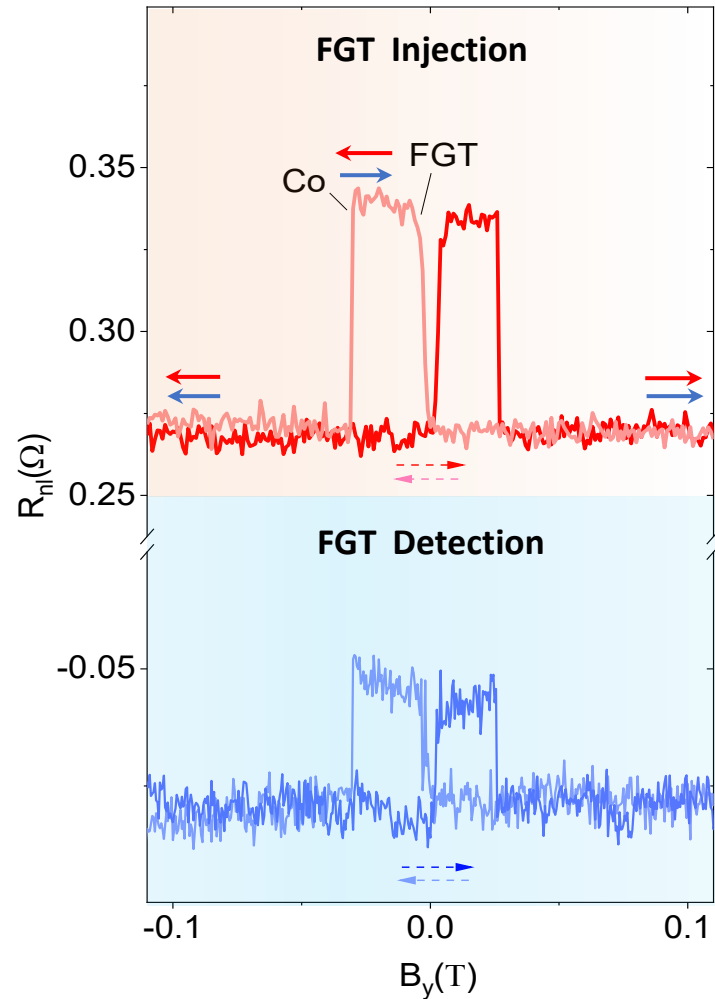
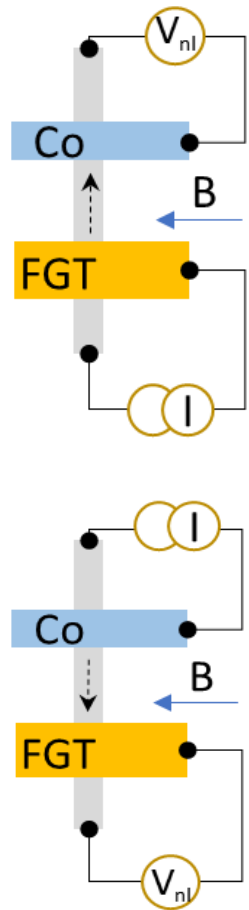
- **vdW magnets for SOT Memory application**
 - ✓ *Field-free SOT magnetization switching*
 - ✓ *All-vdW heterostructures field-free SOT*



Probing vdW magnetic states



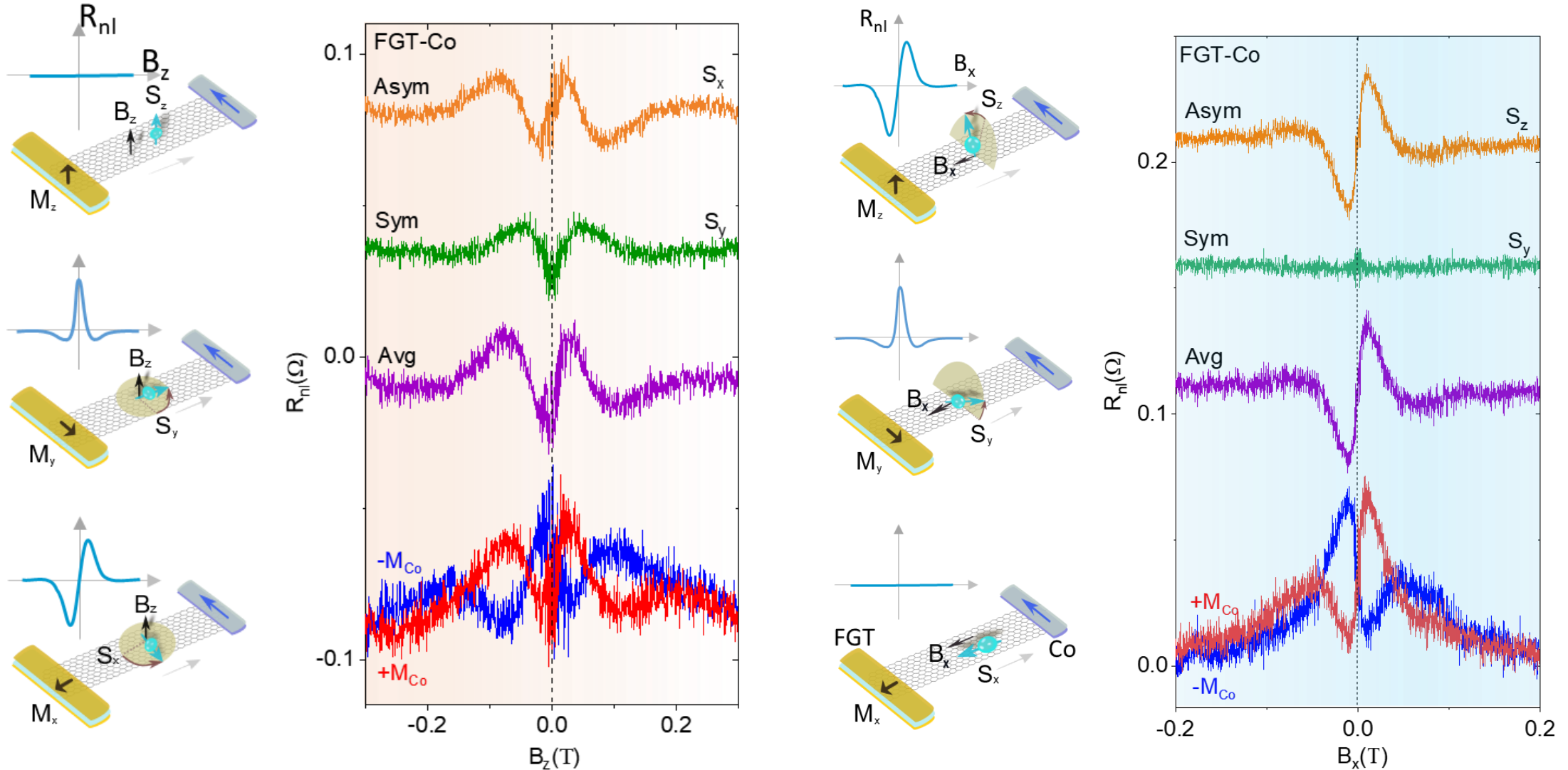
Fe₅GeTe₂/Graphene spin-valve at Room Temperature



- ✓ Robust spin valve operation in FGT/graphene heterostructure
- ✓ Spin-valve signals show the in-plane spin polarization S_y
- ✓ Spin polarization of up to -45 % could be detected at RT

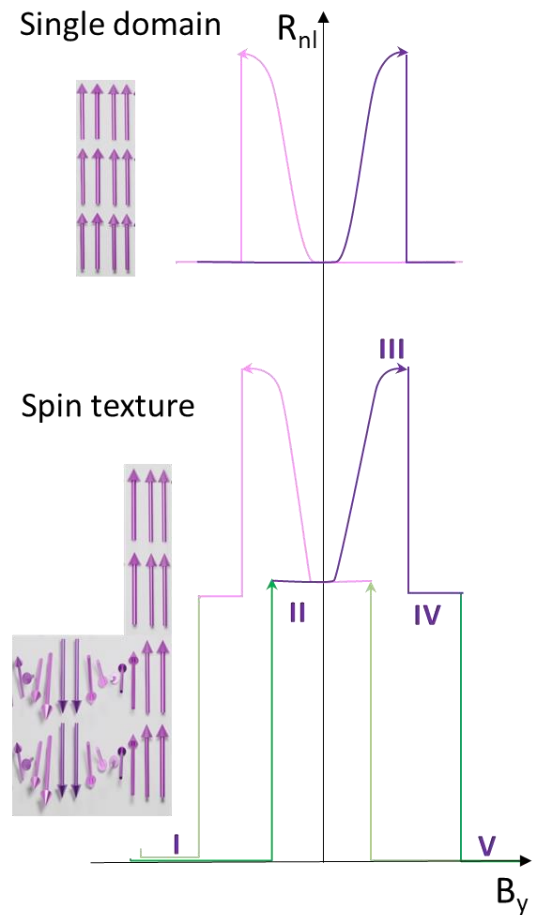
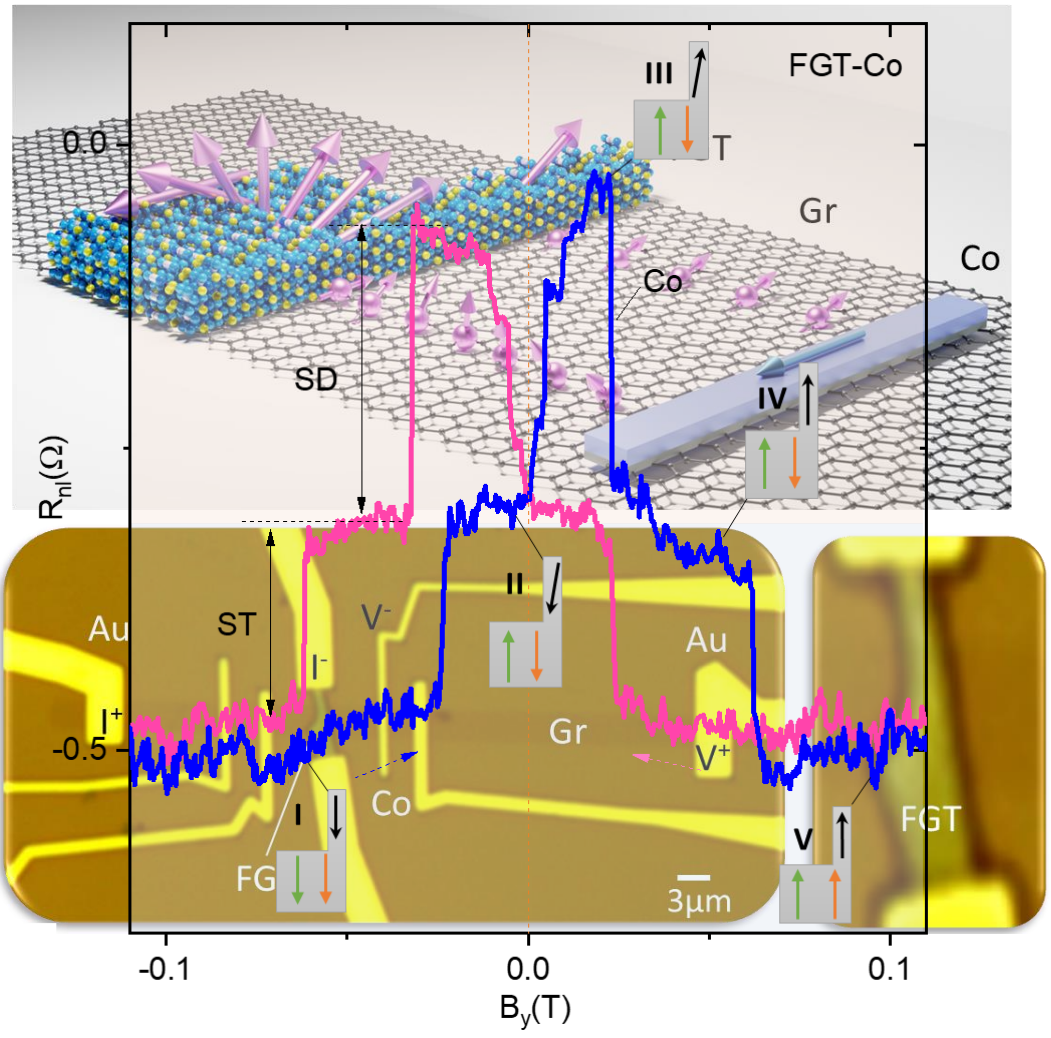
Spin precession in $\text{Fe}_5\text{GeTe}_2/\text{Graphene}$ heterostructure

Hanle precession measurements with B_x and B_z field sweep



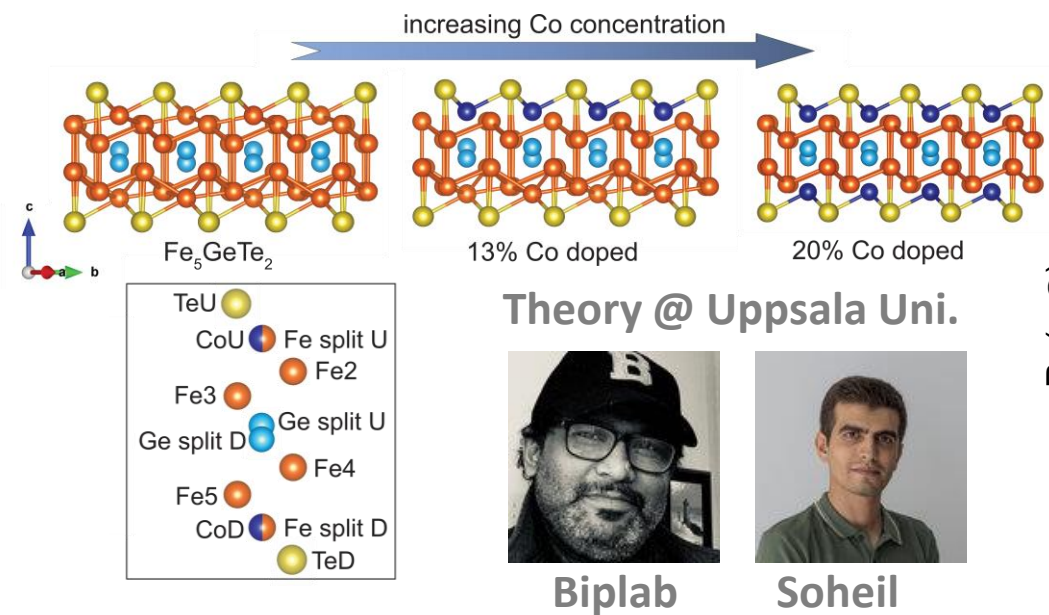
Detection of S_x , S_y and S_z spin components indicates **canted magnetism** of FGT

Electrical detection of spin texture in Constrained/Notched Fe_5GeTe_2

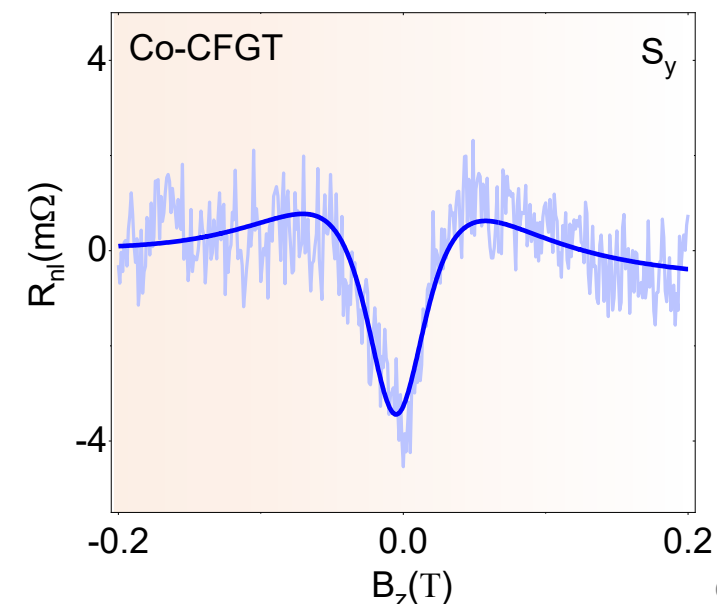
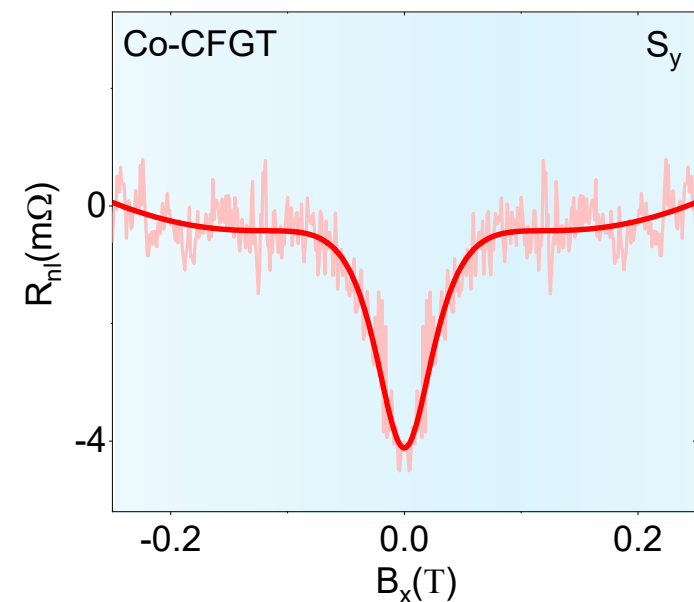
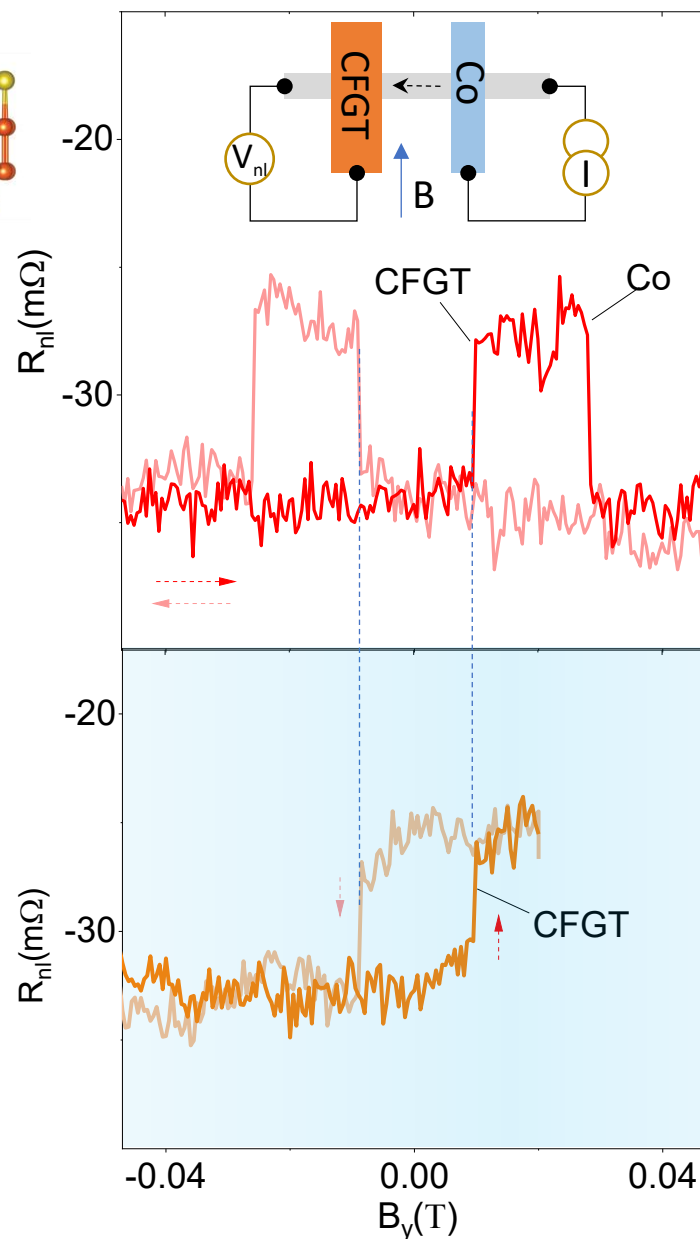
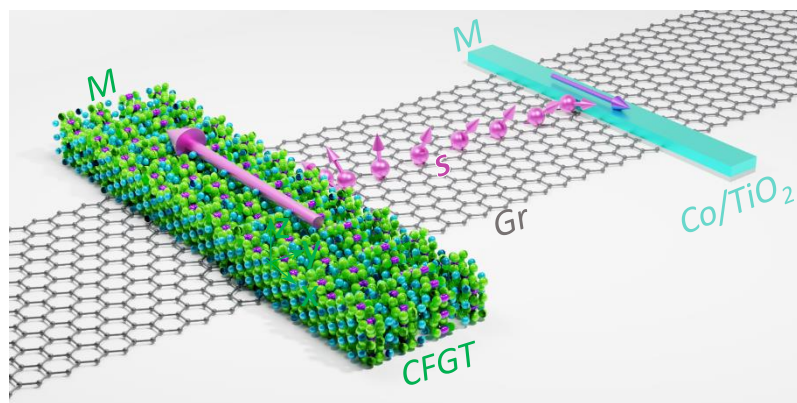


- ✓ Inducing spin texture nucleation sites through constrictions or notches in Fe_5GeTe_2
- ✓ Spin texture imprinted in graphene and be detected
- ✓ Additional switching (stage II and stage IV) – intermediate resistance state due to reorientation of the spin textures
- ✓ Anomalous multi-level spin valve switching – coexistence of spin textures and canted magnetic domain

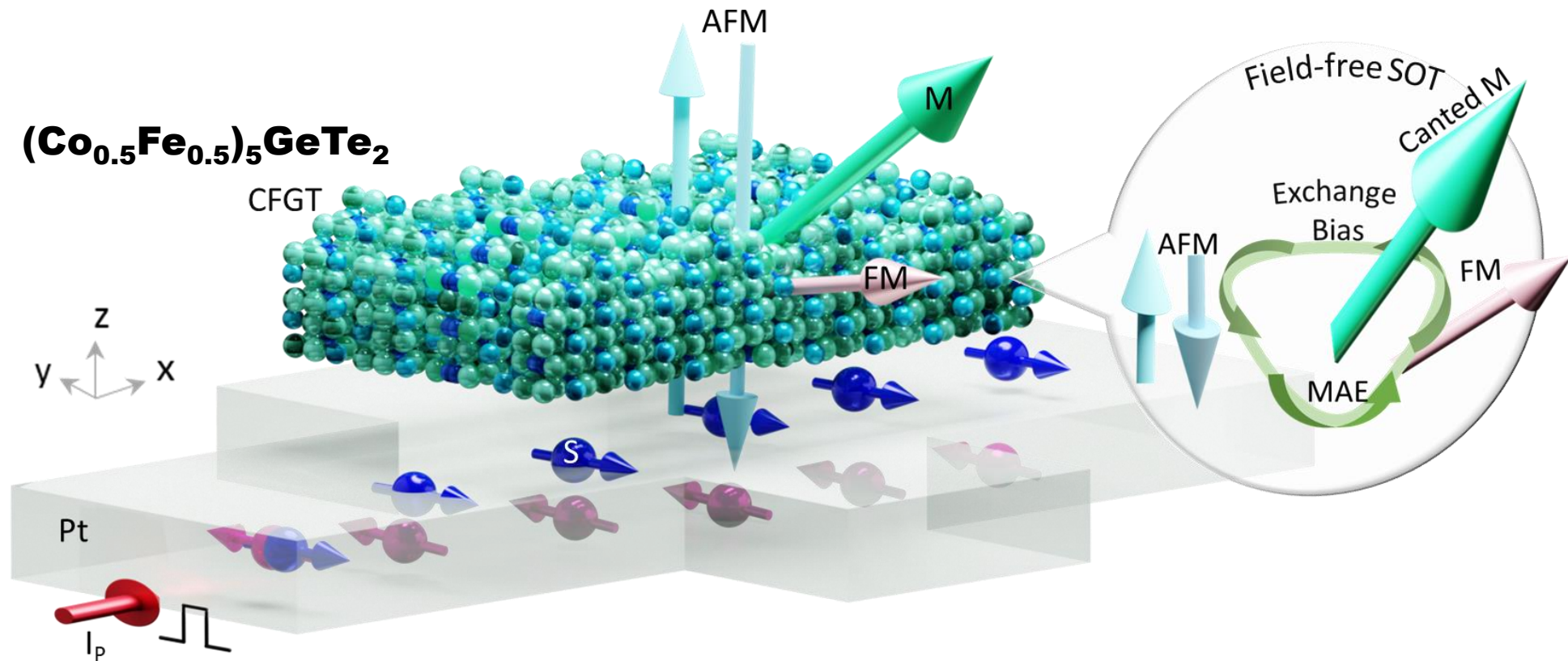
(Co_{0.15}Fe_{0.85})₅GeTe₂ / Graphene spin-valve



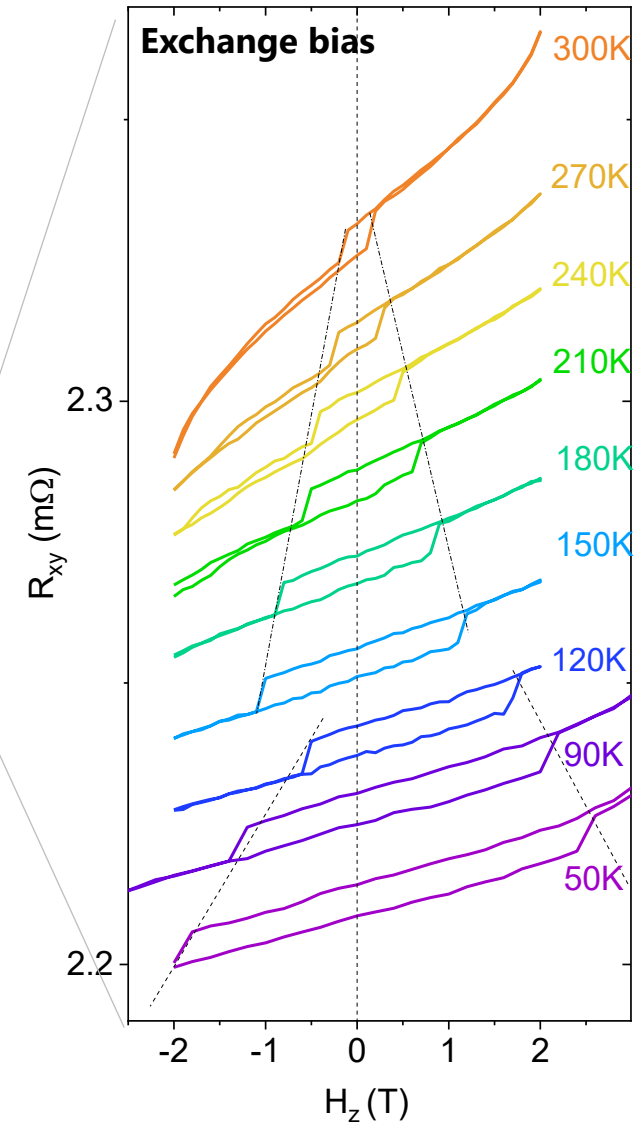
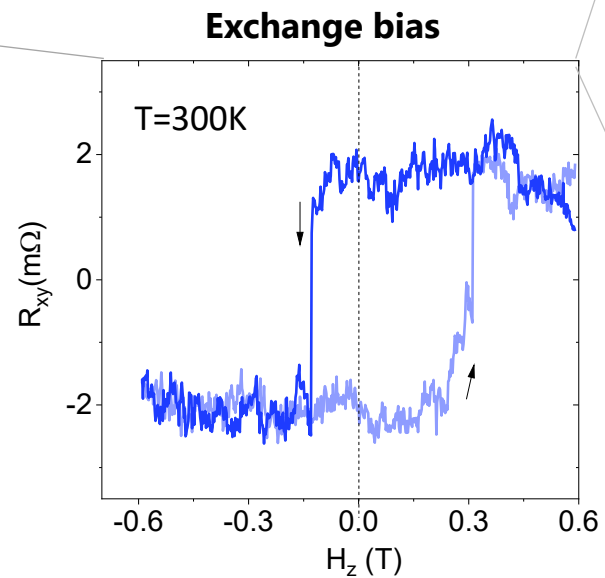
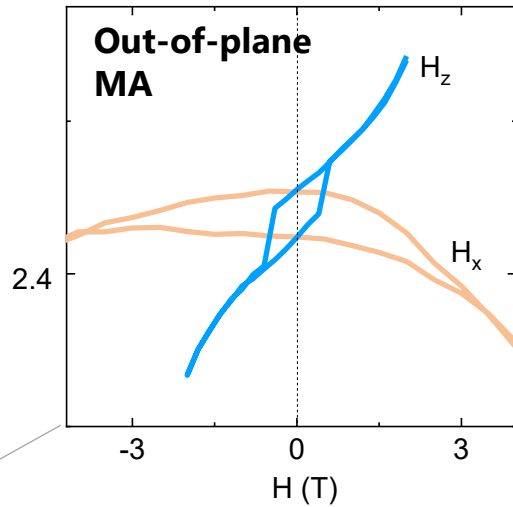
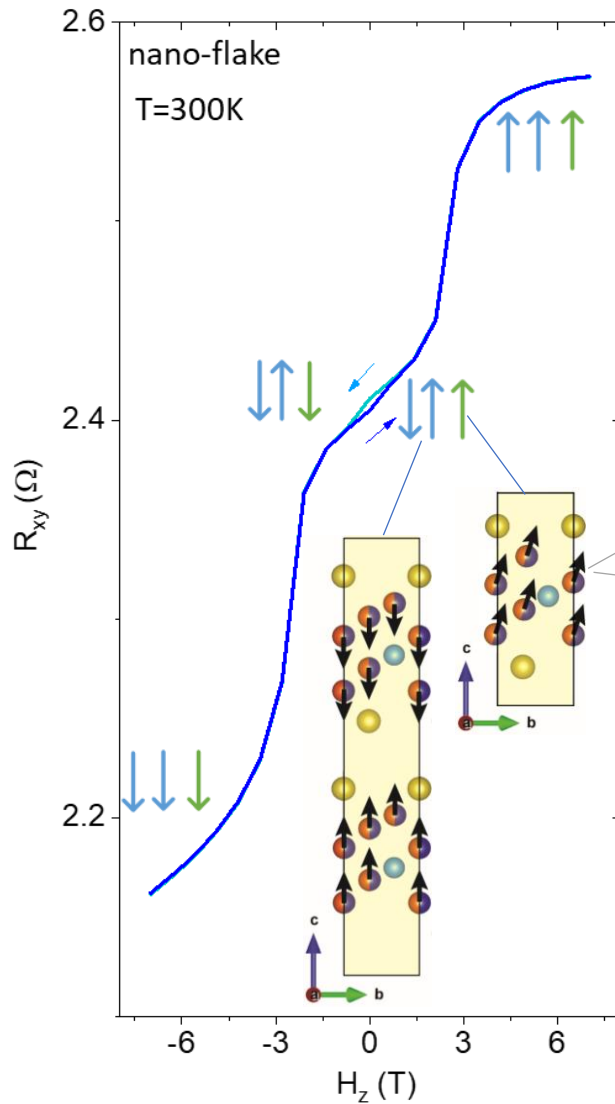
In-plane spin polarization



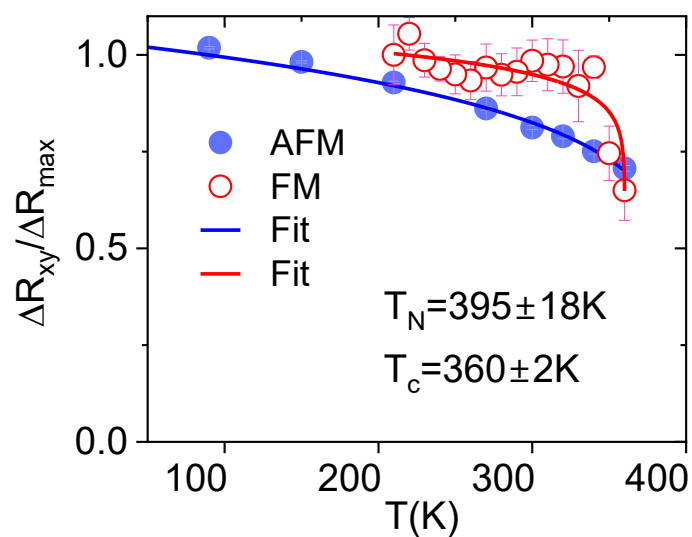
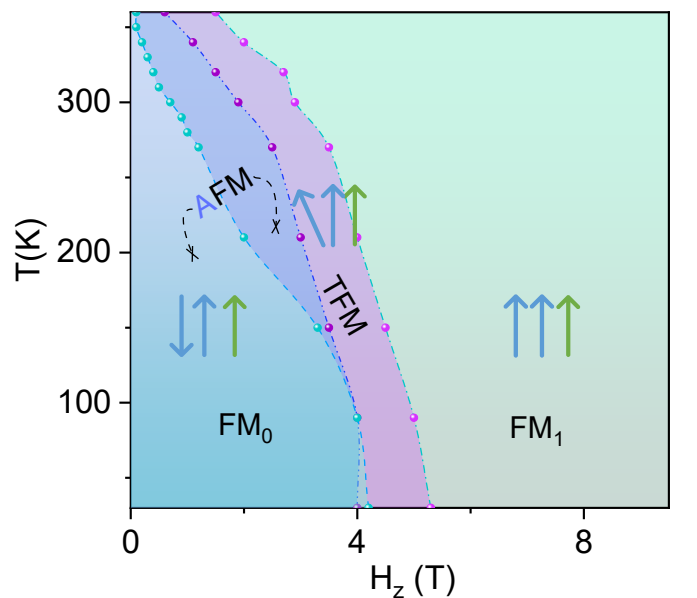
Coexistence of non-trivial van der Waals magnetic orders enabled field-free spin-orbit torque switching



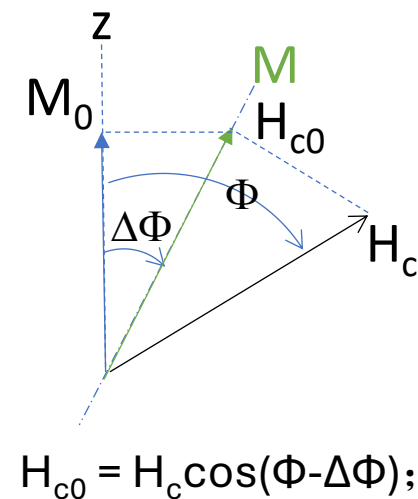
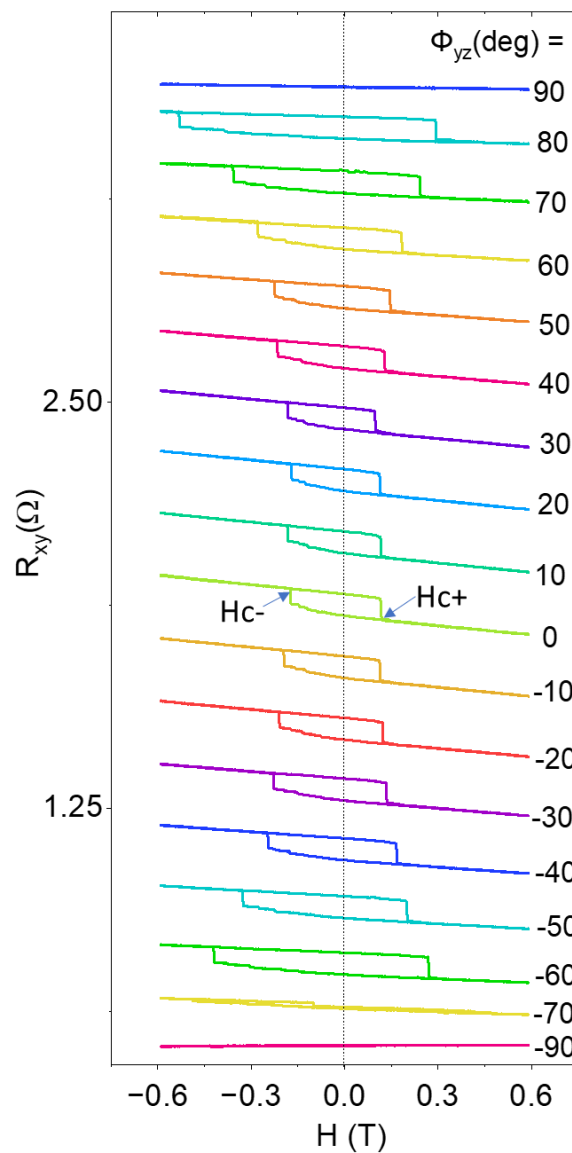
Coexistence of FM and AFM magnetic states



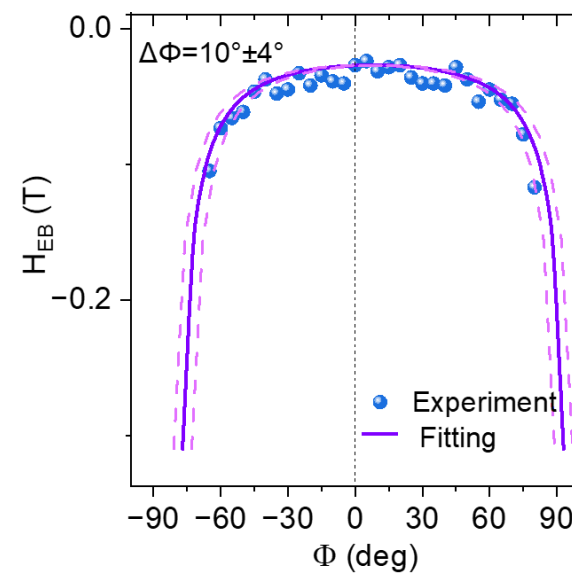
Coexistence of FM and AFM magnetic states beyond RT



Canted Magnetism



$$H_{c0} = H_c \cos(\Phi - \Delta\Phi);$$



$$H_{EB} \sim H_{EB0} / \cos(\Phi - \Delta\Phi)$$

HR-TEM of $(\text{Co}_{0.5}\text{Fe}_{0.5})_5\text{GeTe}_2$

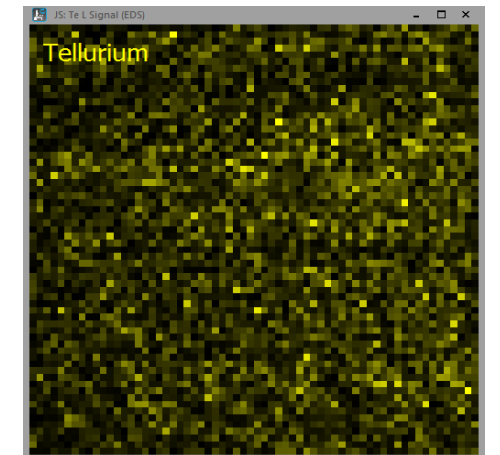
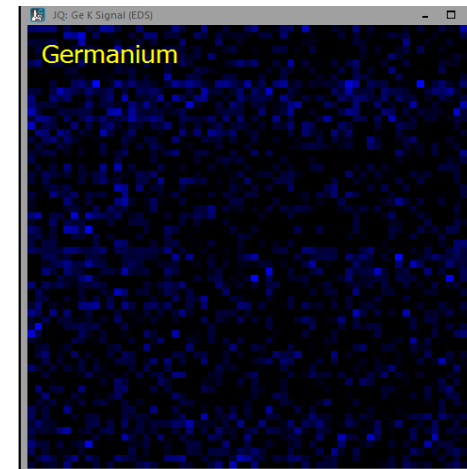
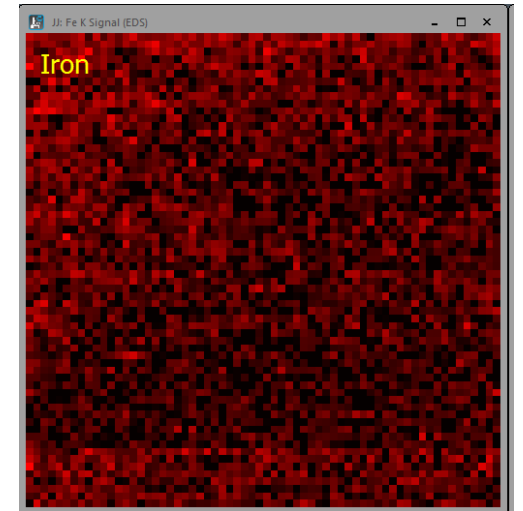
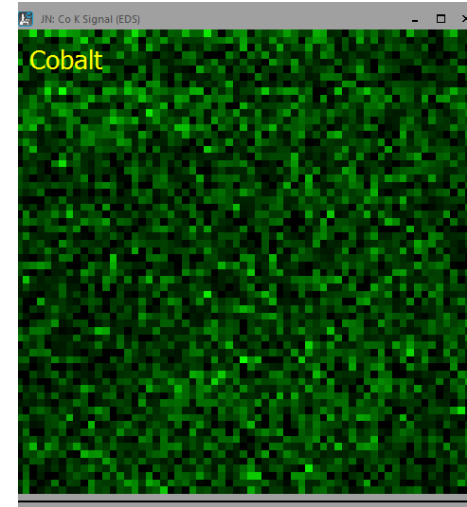
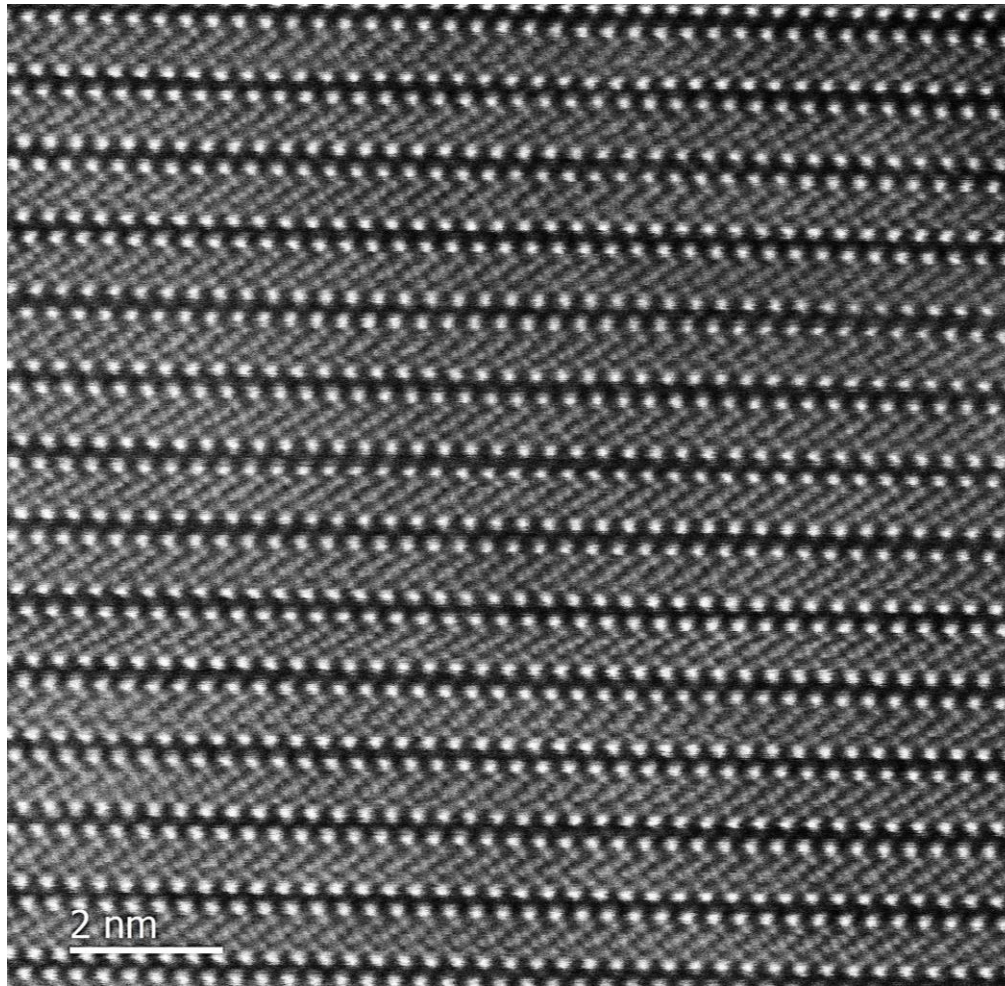
TEM @ Chalmers



Eva Olsson

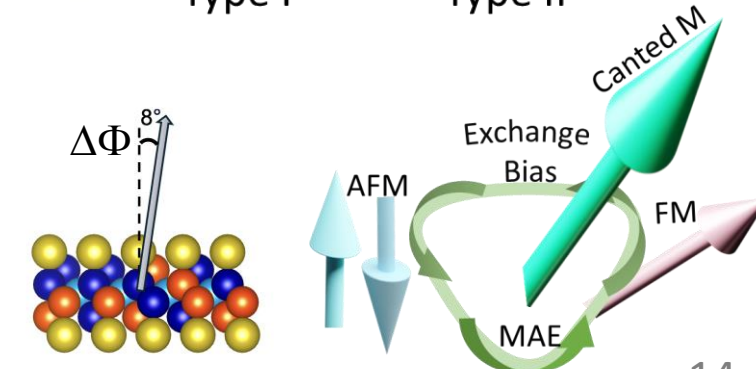
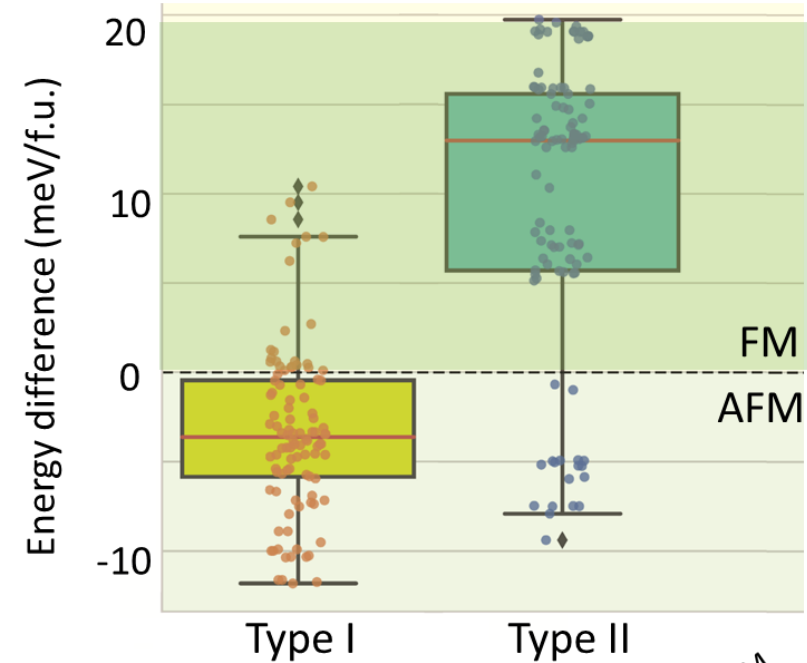
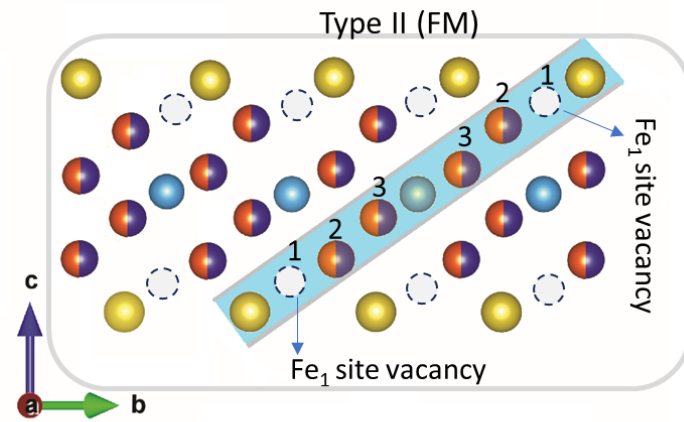
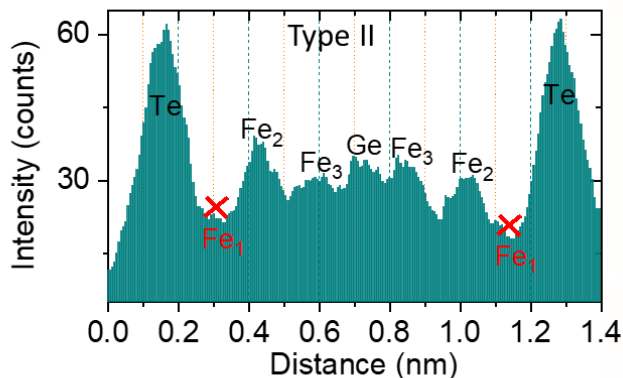
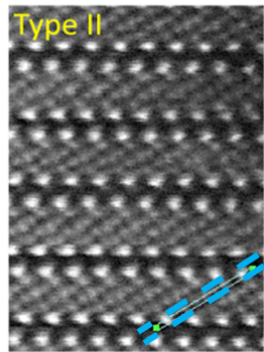
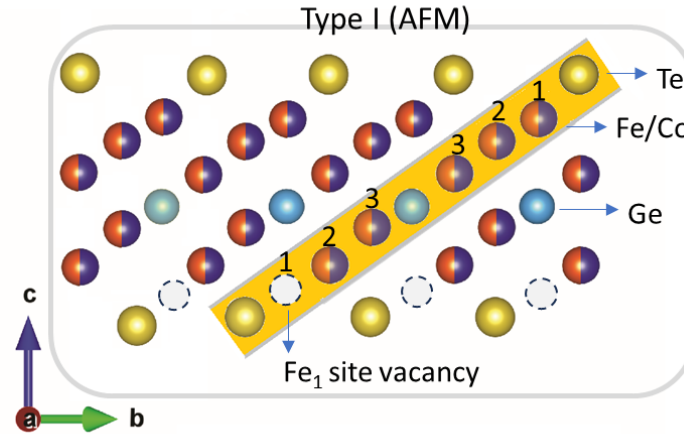
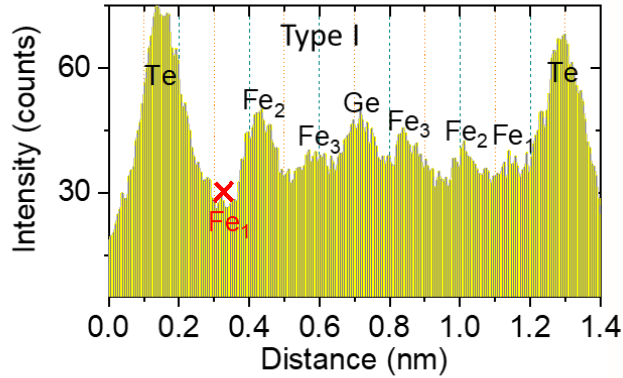
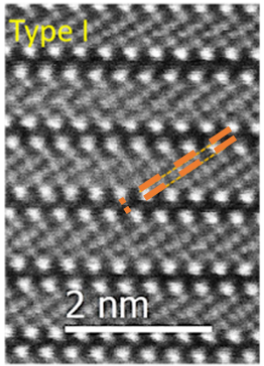


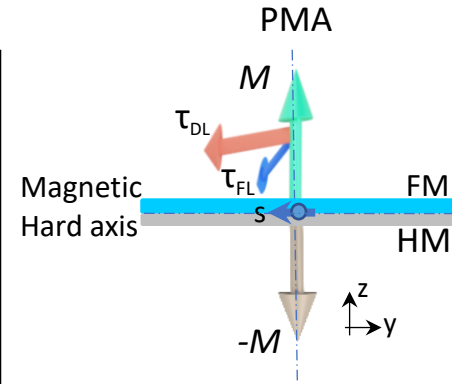
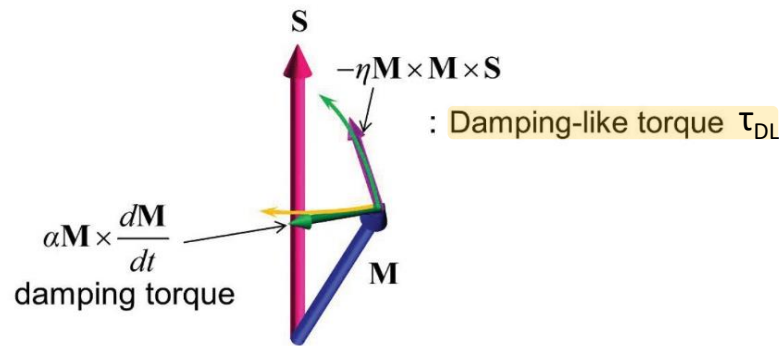
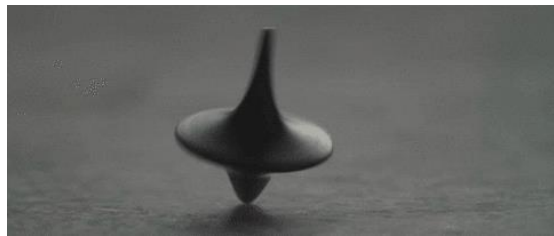
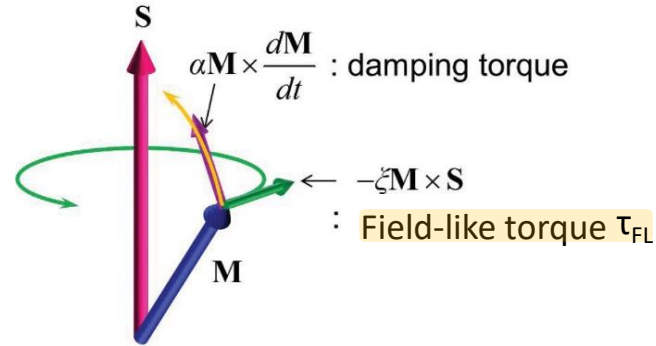
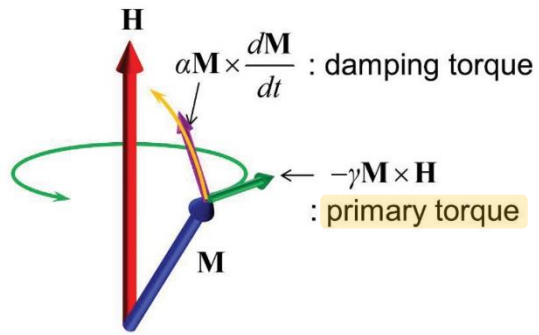
Lunjie Zeng



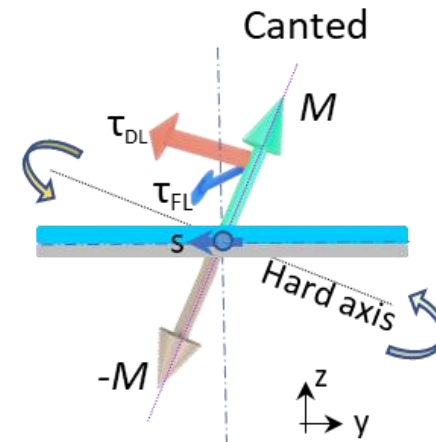
CFGT is mainly in AFM state, but some FM state exists due to vacancies symmetry

Theory @ Prof Biplab group
Uppsala Uni.

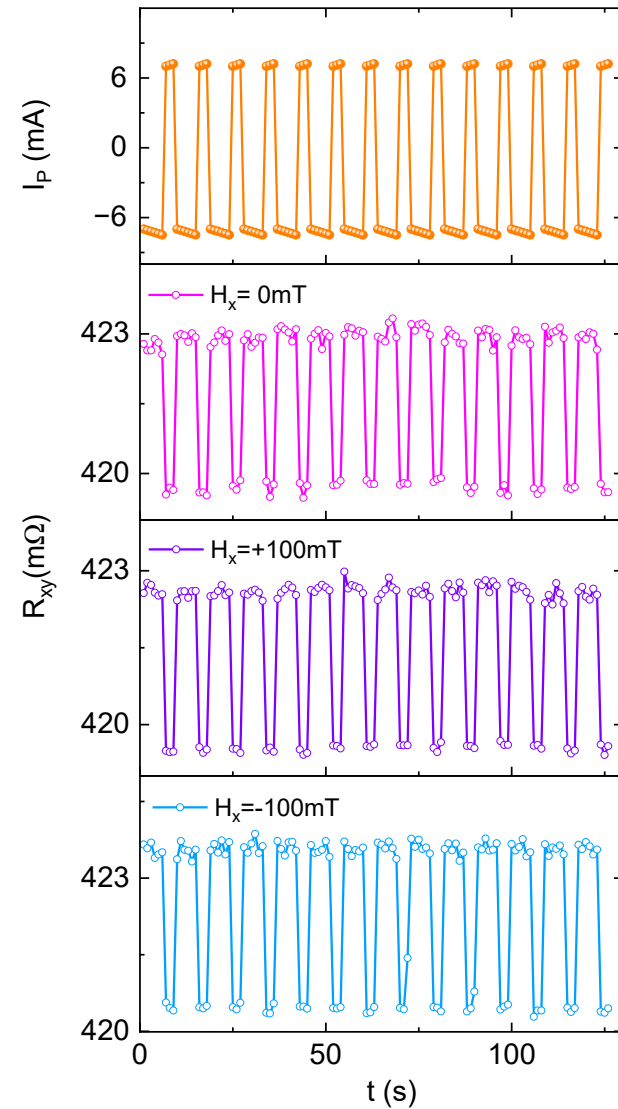
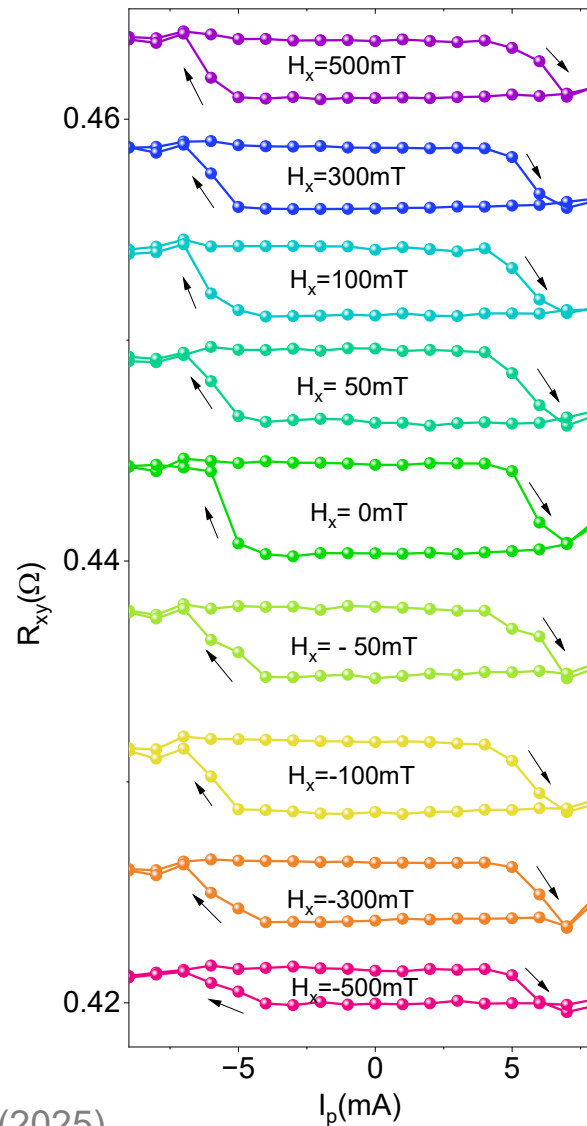
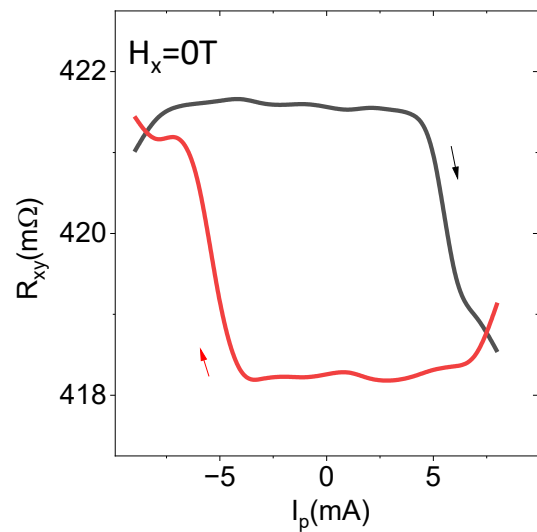
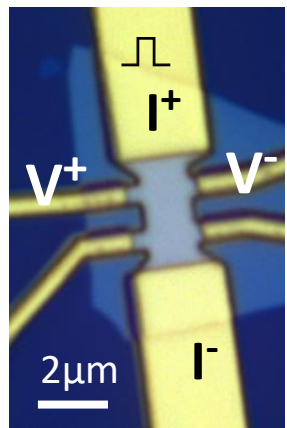
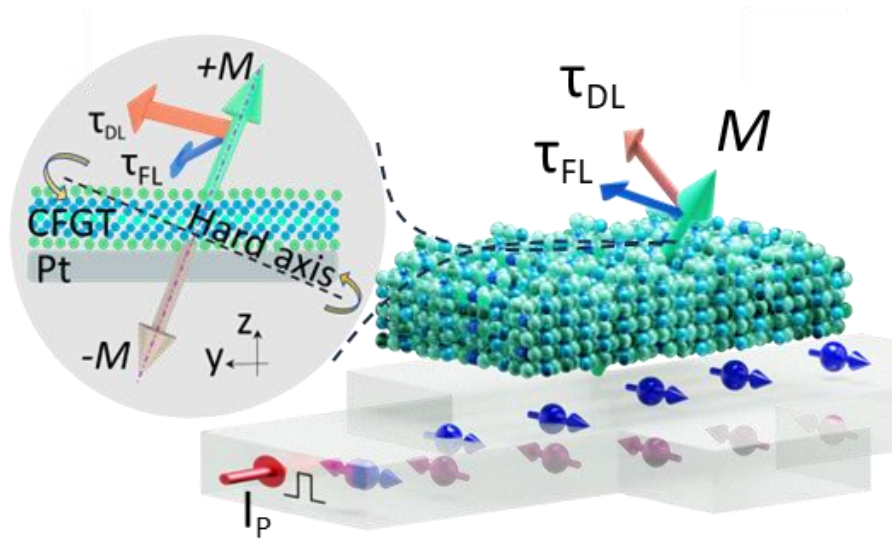


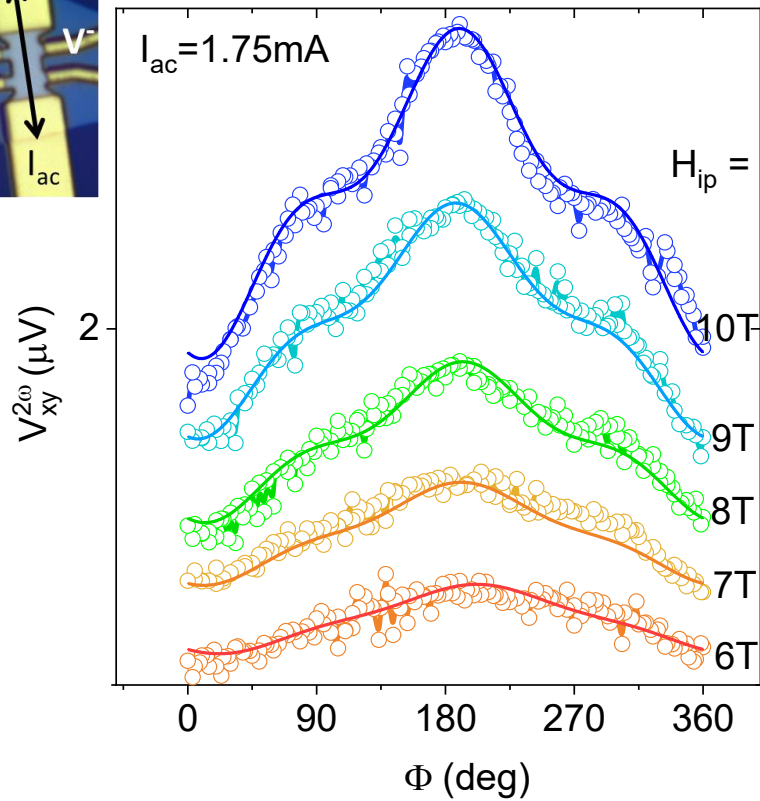
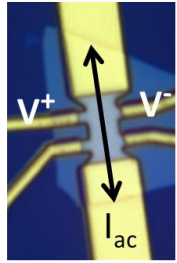


H_x is needed



H_x is NOT necessary for a CMA!

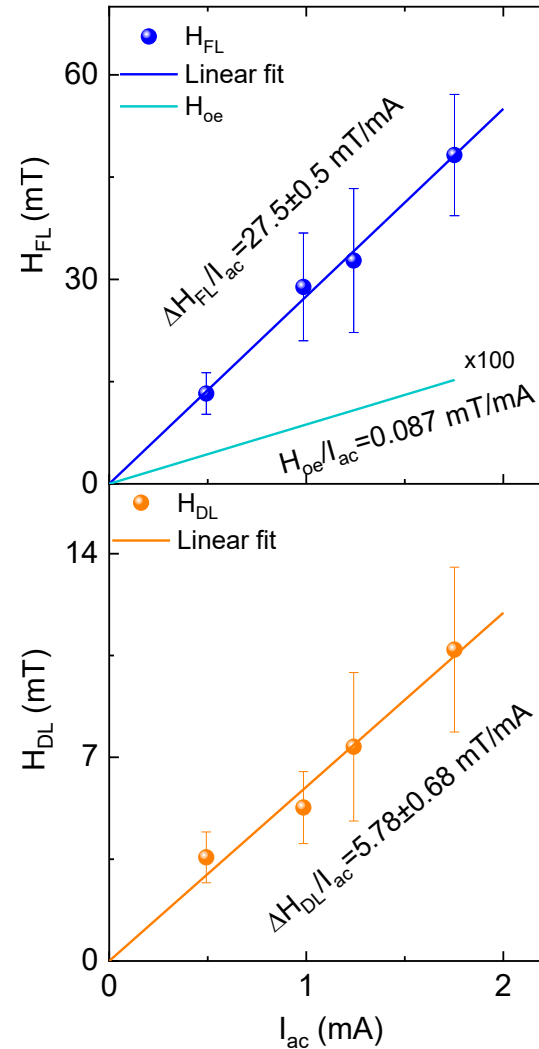




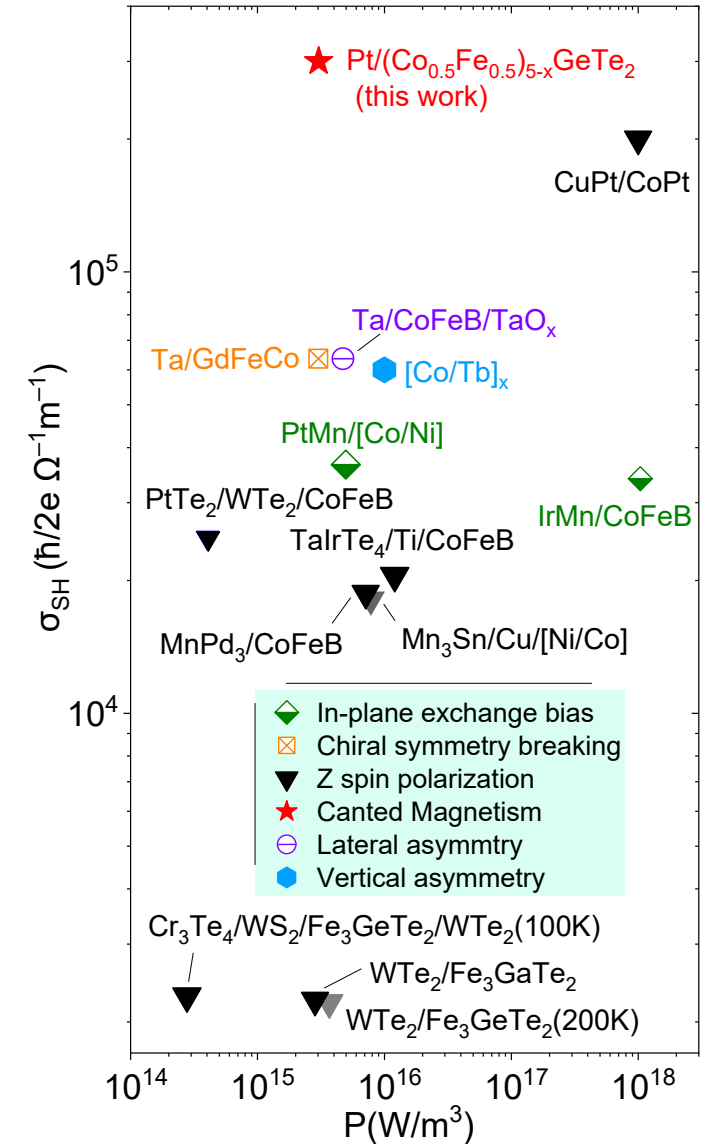
$$V_{xy}^{2\omega} = -A \cos \Phi + B(2 \cos^3 \Phi - \cos \Phi);$$

$$A = V_{AHE} \frac{H_{DL}}{H_{ex} - H_k} + V_{thermal}; \quad \text{DL effective field, thermal contribution}$$

$$B = 2V_{PHE} \frac{H_{FL} + H_{oe}}{H_{ex}}; \quad \text{FL effective field and Oersted field}$$



filed free SOT devices

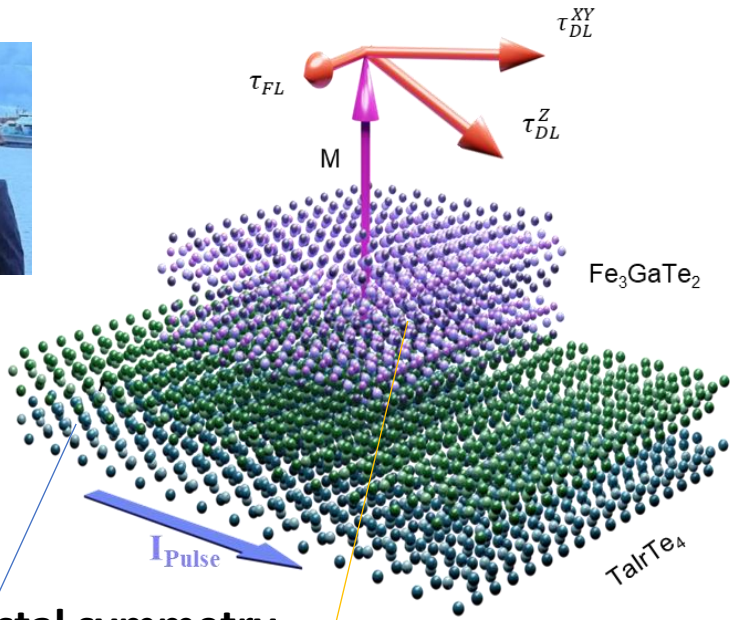


All-vdW heterostructure Spin-Orbit Torque

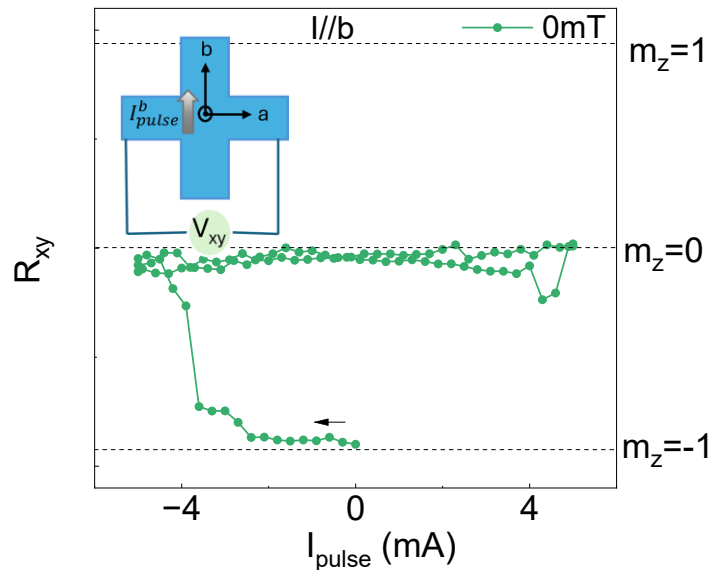
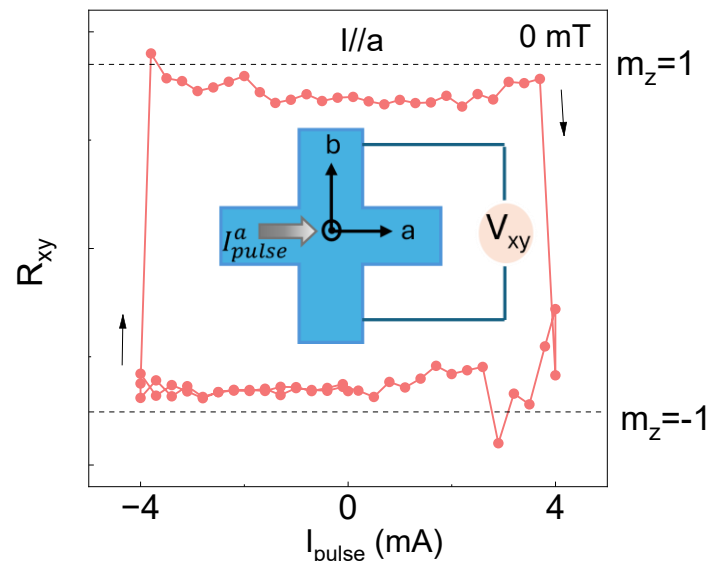
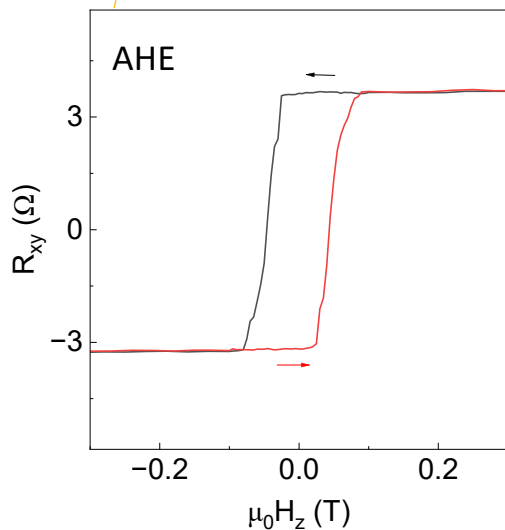
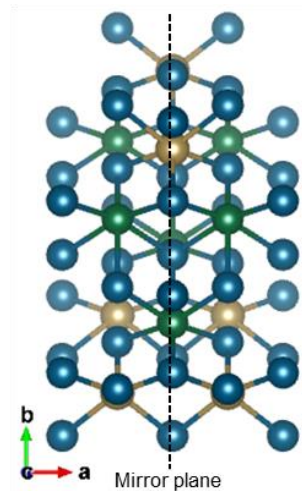
Field-free Deterministic spin-orbit torque switching at room temperature



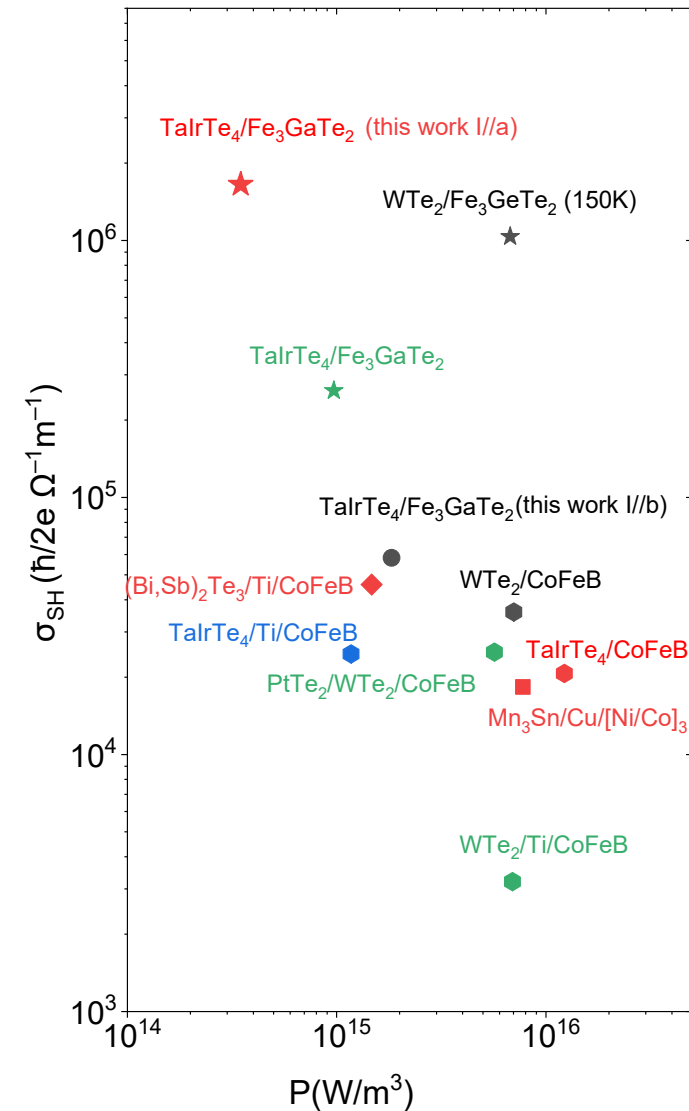
Lalit



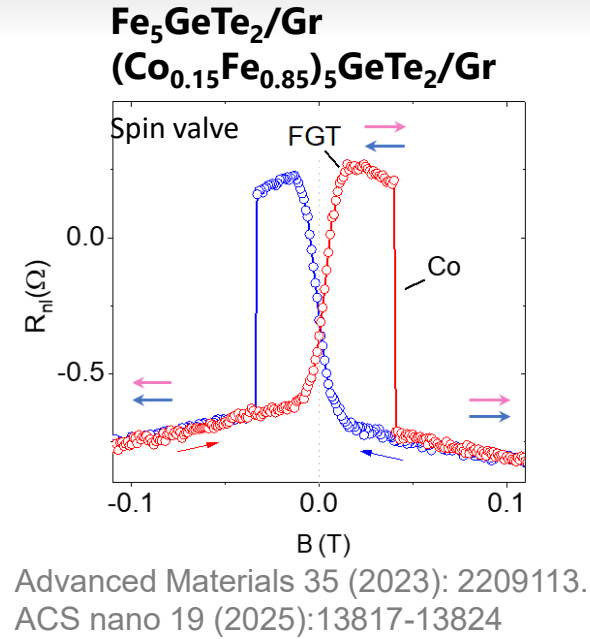
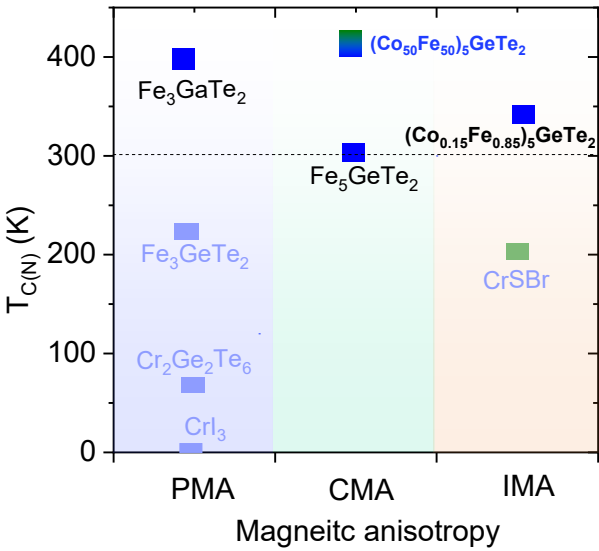
Lower crystal symmetry



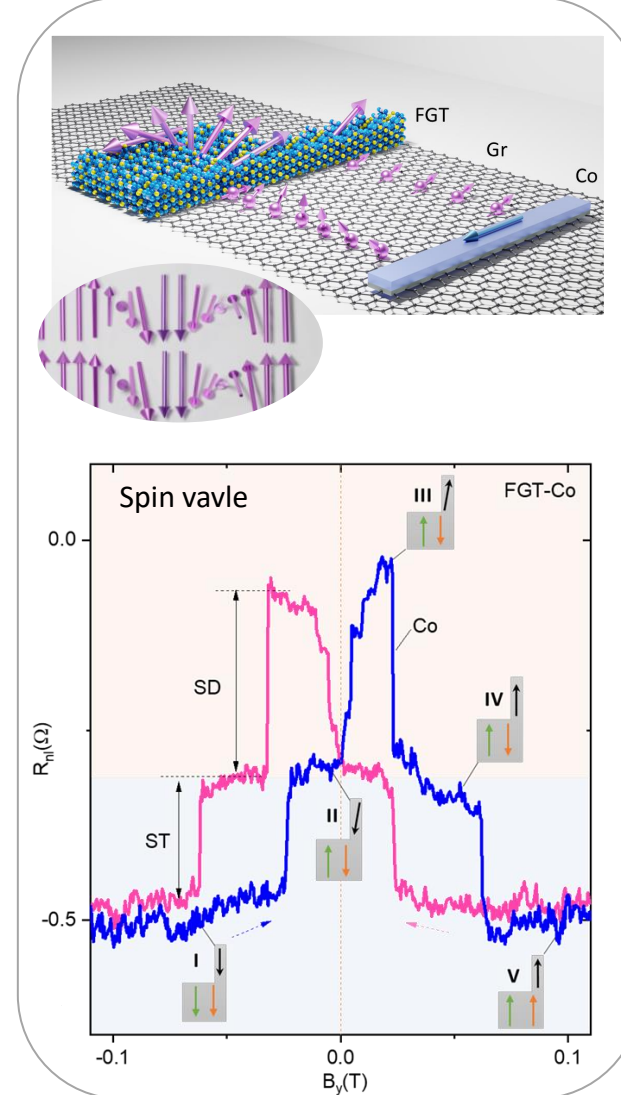
field free SOT devices



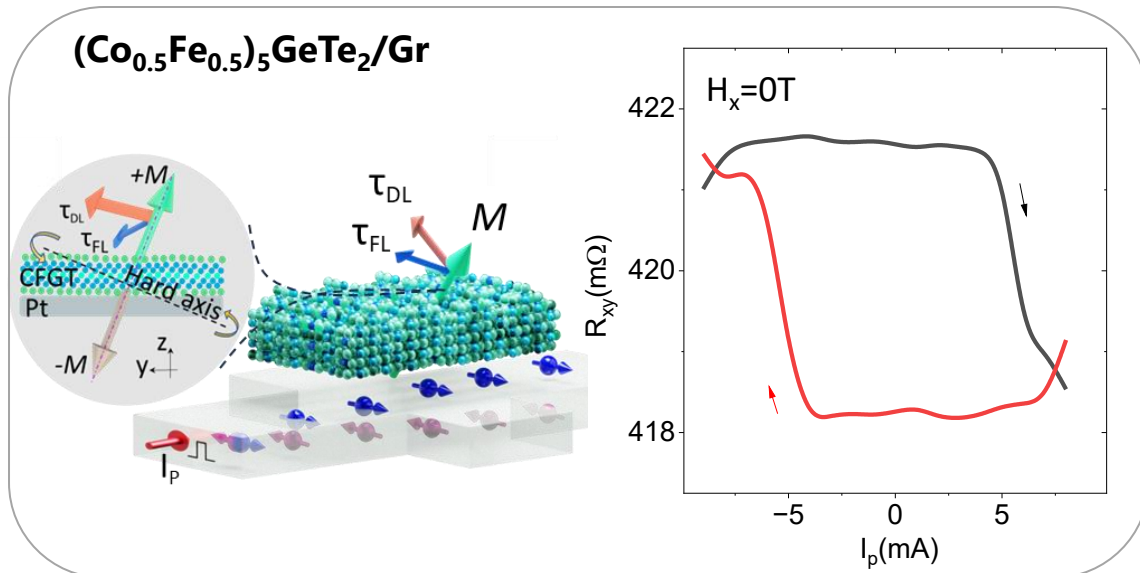
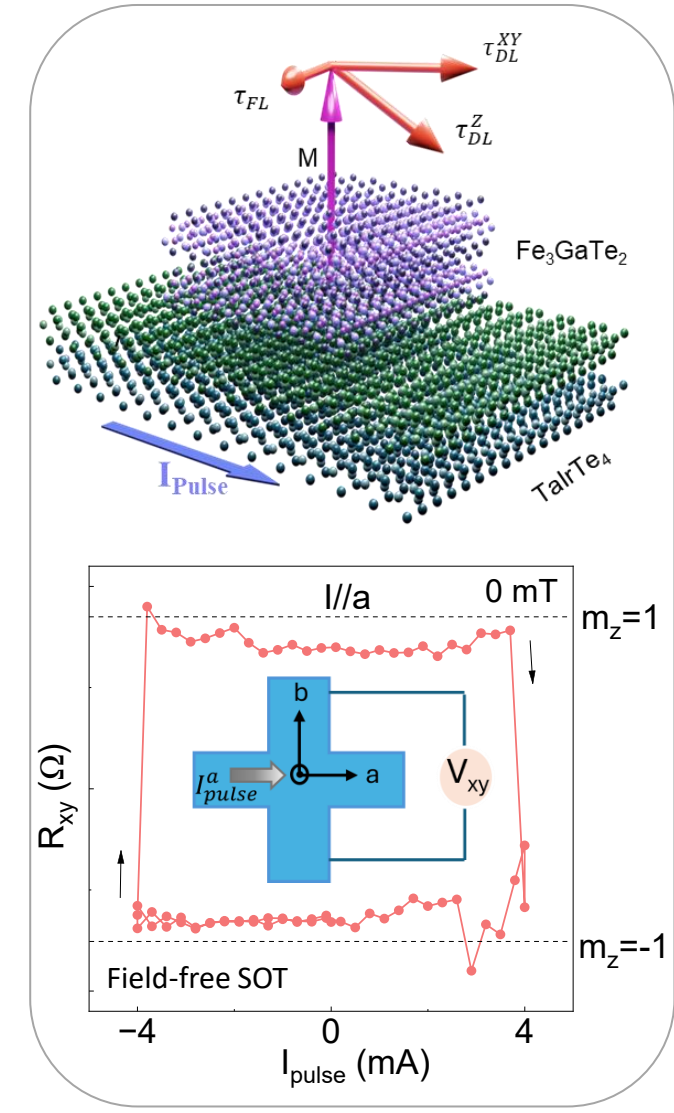
Summary



Electrical detection of spin texture in Constrained/Notched Fe_5GeTe_2



All 2D SOT $\text{Fe}_3\text{GaTe}_2/\text{TaIrTe}_4$



Thank you!



CHALMERS
UNIVERSITY OF TECHNOLOGY