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INTERFACIAL EFFECTS OF ALTERMAGNETIC RUO_2 WITH FERROMAGNETS AND HEAVY METALS

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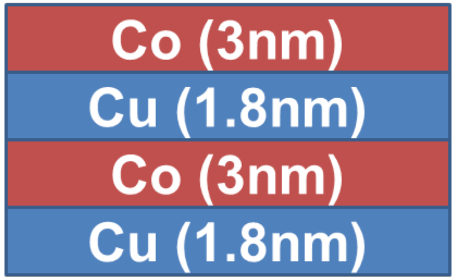
Collaborations with Uni Mainz, TU Dresden, TU Berlin, …

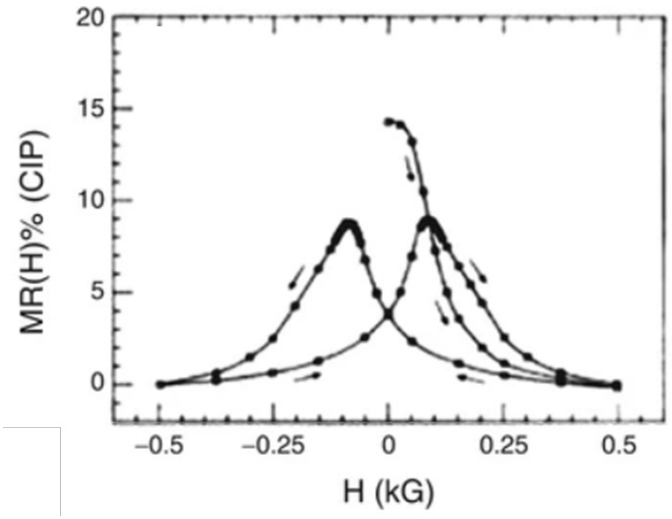
Outline

- **Introduction Heterostructures / Multilayers**
  - **New features with in situ resistance and magnetoresistance measurements**
  - **Sensing applications**
- **Altermagnets**
  - **Growth of RuO_2**
  - **Properties of RuO_2 / Permalloy**
  - **Harmonic Hall investigation of torques in RuO_2 / Permalloy**
  - **Neél vector switching in RuO_2/Pt**
  - **Magnetic tunnel junctions RuO_2/MgO/CoFeB**
  - **Growth of Mn_5Si_3**
- **Outlook**

Introduction: Examples for heterostructures: $(Co/Cu)_X$

Co/Cu multilayers





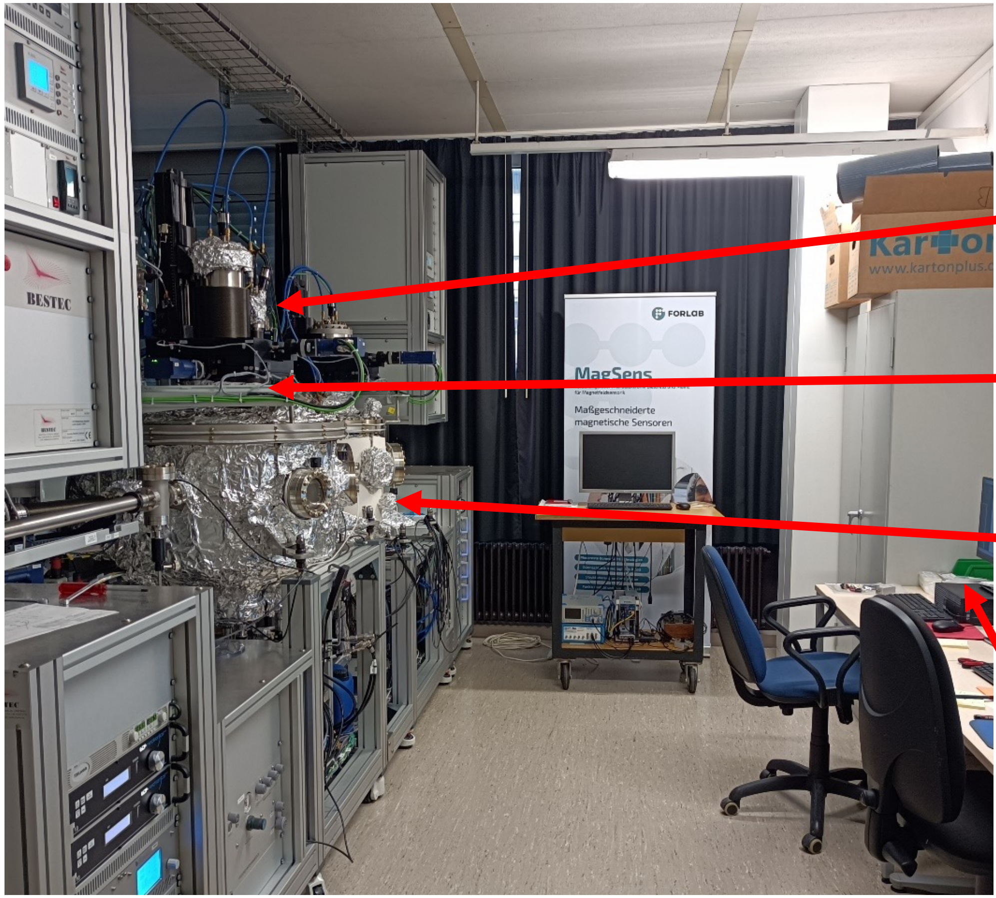
J. Appl. Phys. 75, 362–367 (1994), Phys. Rev. B 87, 134406 (2013)

Bass, J. (2016) in: Xu, Y., Awschalom, D., Nitta, J. (eds) Handbook of Spintronics. Springer

Exhibit Giant Magnetoresistance

→ Characterize interfaces

Examples for heterostructures: $(Co/Cu)_X$



New machine:

3-D Magnetic ac-field at 10-20 Hz

Sample holder with in situ resistance measurement

Sputter- and MBE chambers

Fast electronics to shuffle 5000 data points per sec over hours

Complete field loop R vs. $\vec{H}$ in 0.2 sec

→ From one field loop to the next, we have about 0.1 monolayers thickness increase

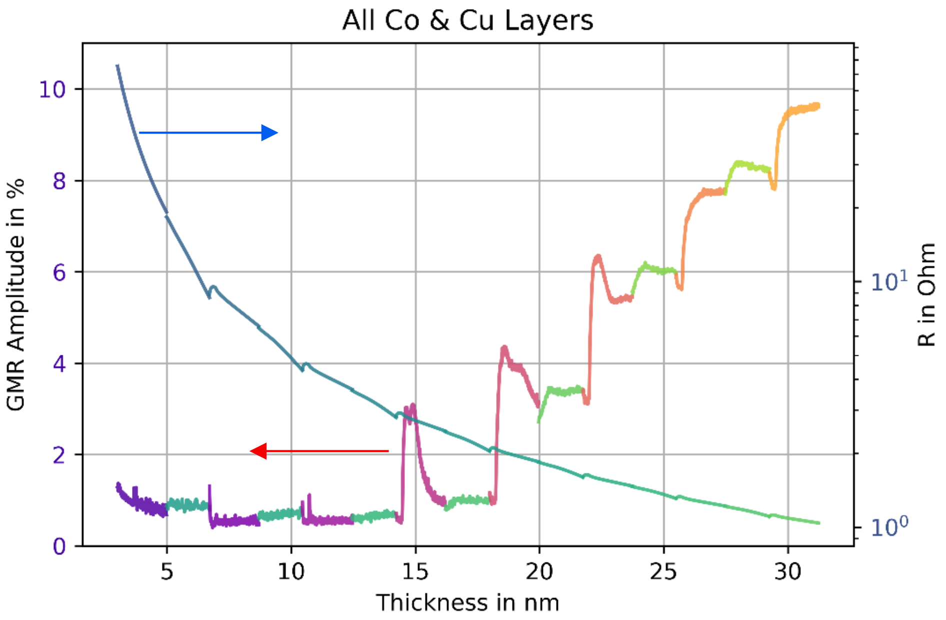
Bundesministerium für Bildung und Forschung

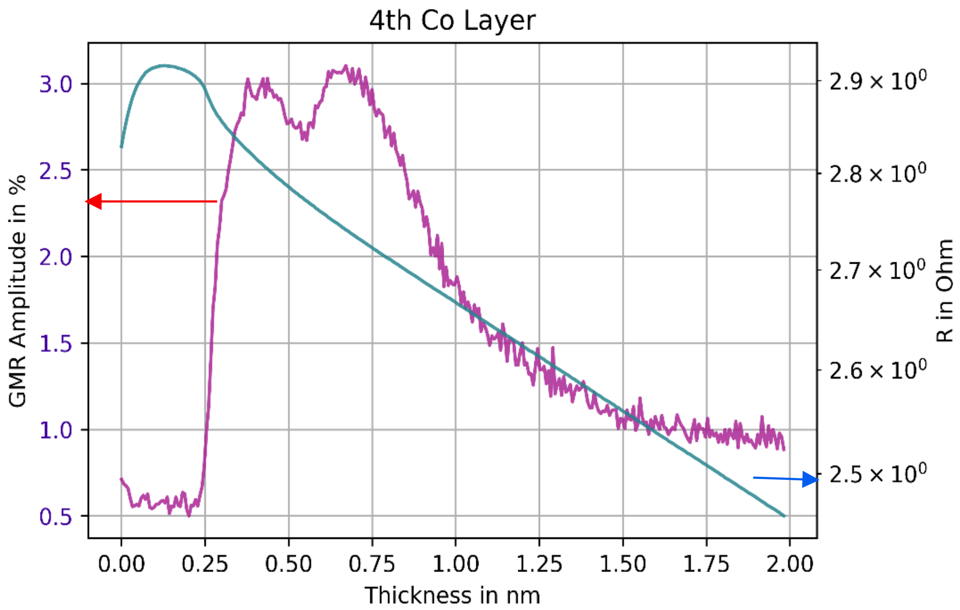
MagSens
Forschungslabore Mikroelektronik Deutschland

Kläui (UMZ), Reiss (UBI)

Examples for heterostructures: (Co/Cu)$_X$

In situ magnetoresistance characterization

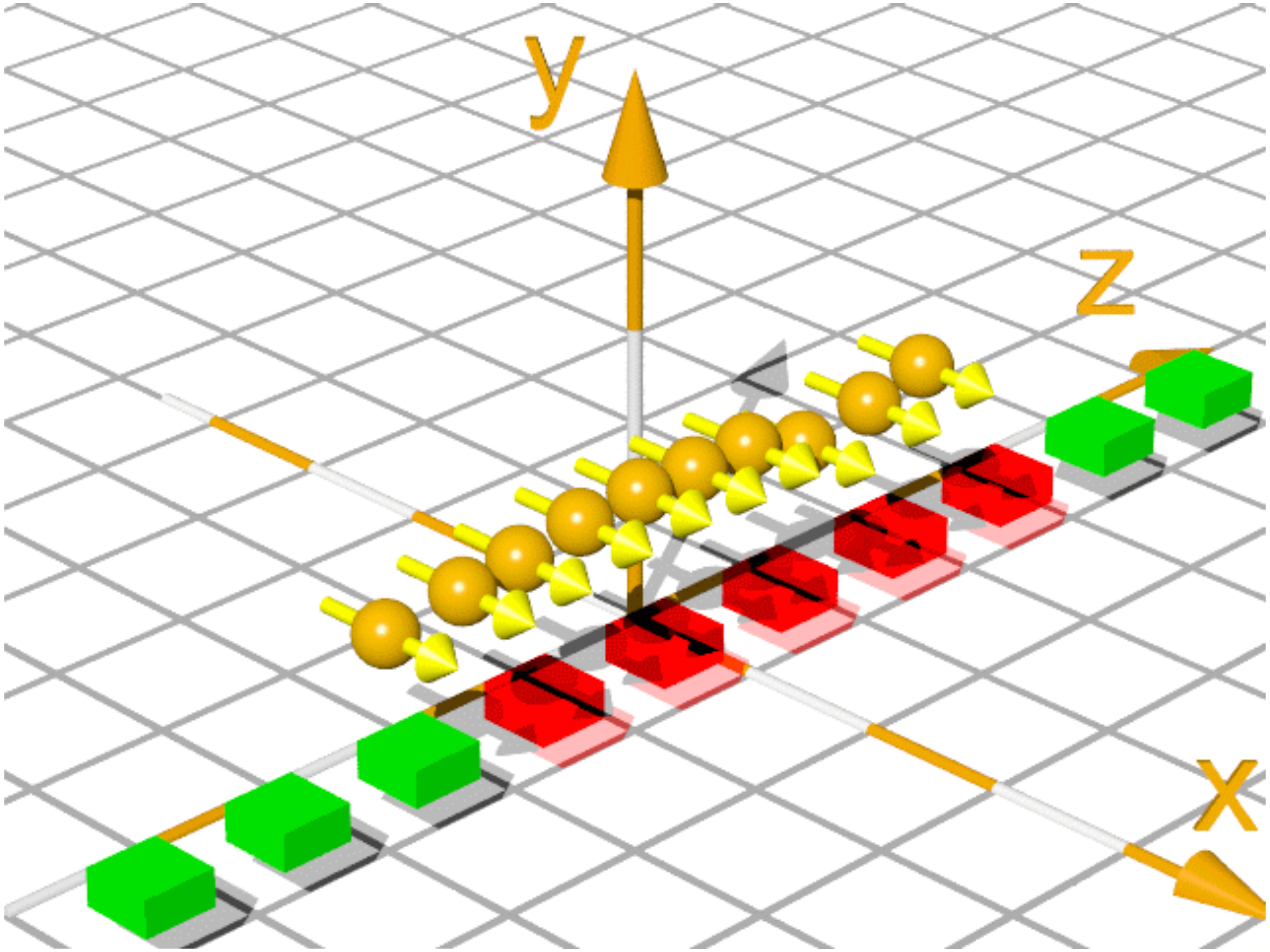


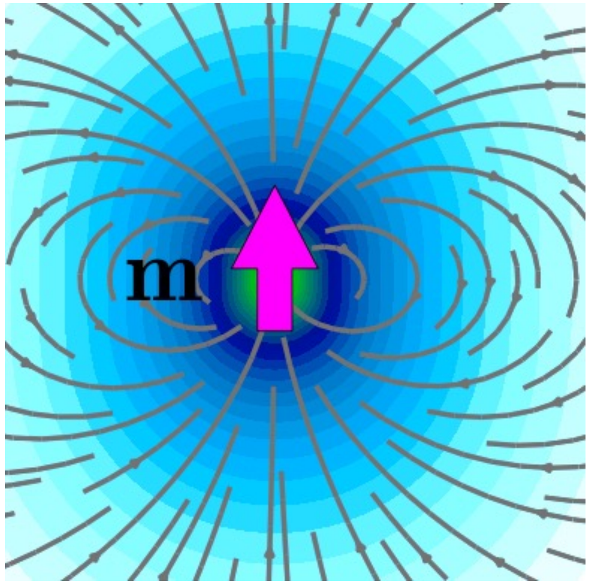


- **Unexpected behavior for d_{Co} lower than about 1nm**
- **Pronounced maximum (? oscillation) with Co thickness**
- **GMR also increases with the first few atoms of Cu**
- **Explanation pending ..**

Sensing, memories ..

- Detect the position and movement of magnetic particles

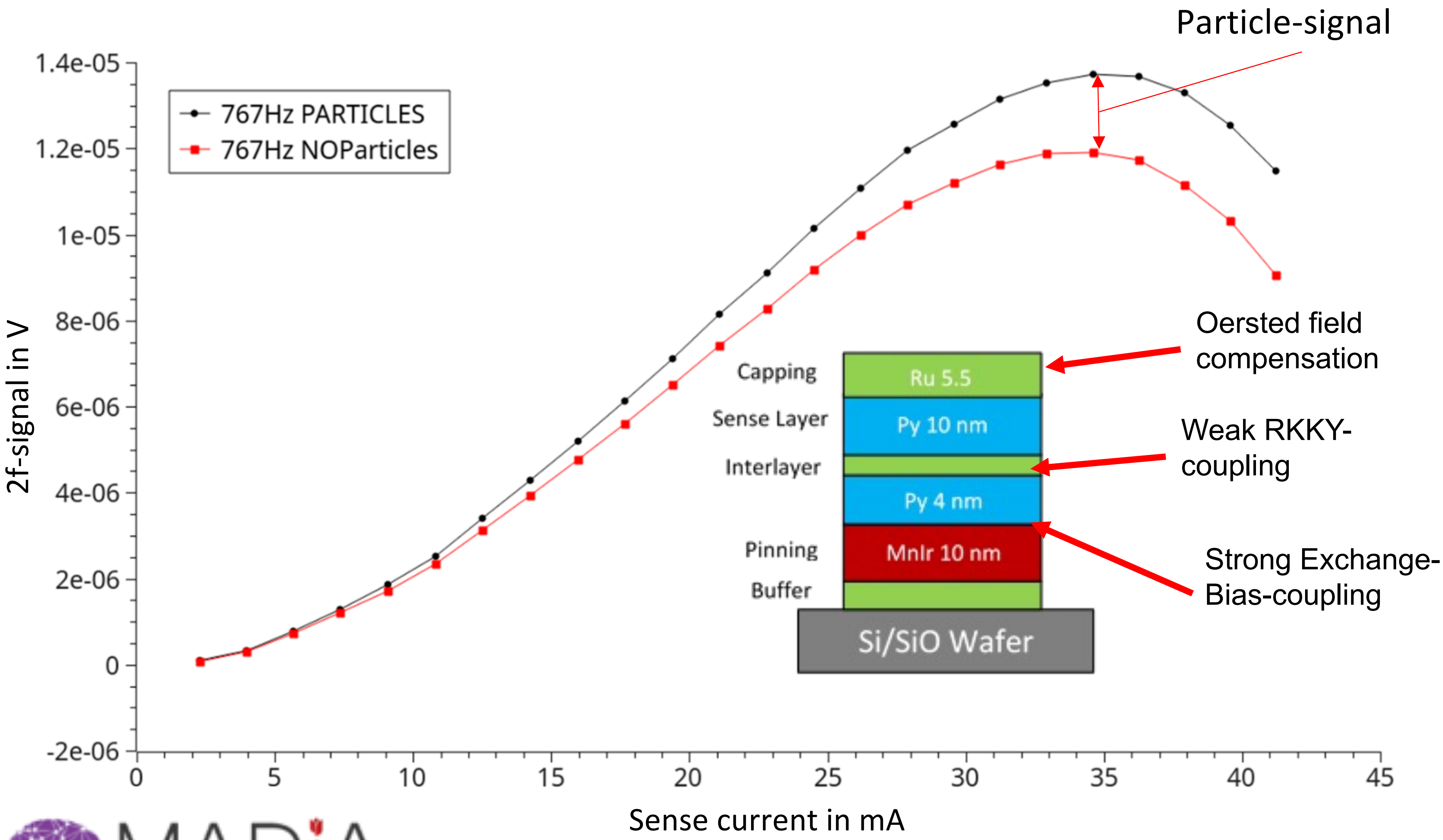




MADiA
MAgnetic DIagnostic Assay
for neurodegenerative diseases

- By sensing the stray field of magnetic nanoparticles

Sensing of magnetic particles & biomolecules



MADiA
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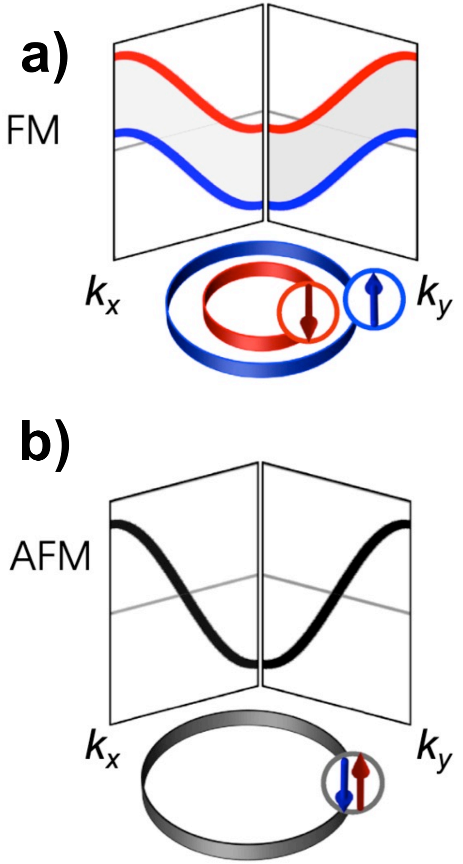
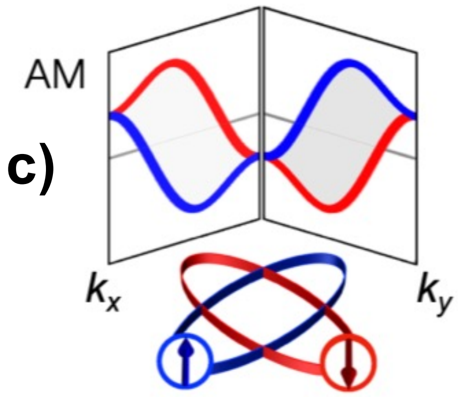
for neurodegenerative diseases

Altermagnets: Why interesting?



a) Spin split band structure of a simple ferromagnet (FM)
b) Band structure of a simple Antiferromagnet



c) Spin split band structure of a model altermagnet (FM)

→ **No net spin polarization**

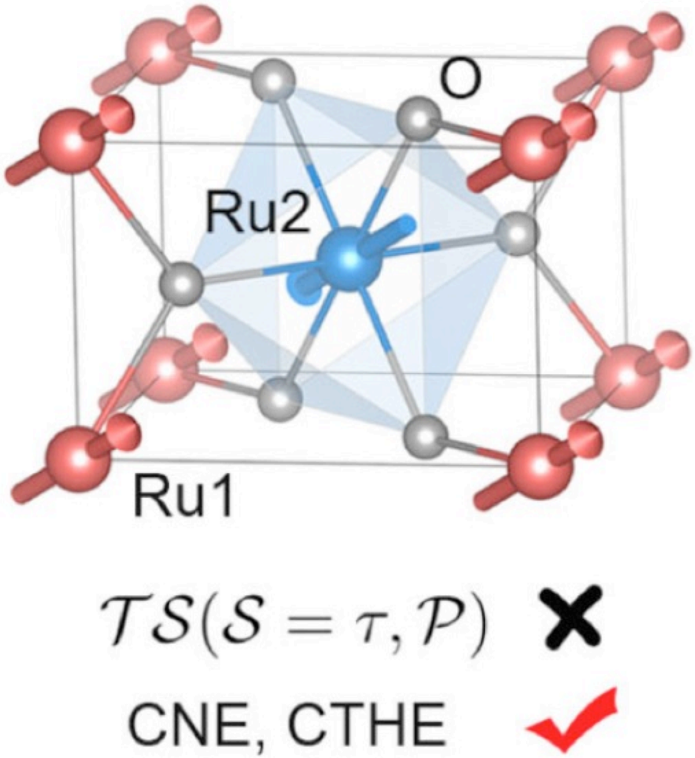
→ **But in this case spin polarized currents depending on direction.**

→ **Interesting for many phenomena:**

- **Tunneling Magnetoresistance**
- **Spin Orbit Torque #1 (switching of a FM)**
- **Spin Orbit Torque #2 (switching of an AM)**
- **… and many more**

L. Bai, W. Feng, S. Liu, L. Šmejkal, Y. Mokrousov, Y. Yao, Altermagnetism: Exploring New Frontiers in Magnetism and Spintronics. Adv. Funct. Mater. 2024, 34, 2409327. https://doi.org/10.1002/adfm.202409327

Altermagnets: Why interesting?



Crystal structure and magnetic moments (Ru) of RuO_2 (tetragonal lattice with different surroundings of the two Ru sites).

Reason for magnetic ordering is not primarily spin-orbit coupling, but due to crystal symmetry → expected to be robust with respect to contamination, doping etc.

But magnetic order for RuO_2 is also reported as fragile !

A. Smolyanyuk, I.I. Mazin, L. Garcia-Gasull, R. Valentí, Fragility of the magnetic order in the prototypical altermagnet RuO_2, Phys. Rev. B 109, 1345424 (2024)

L. Bai, W. Feng, S. Liu, L. Šmejkal, Y. Mokrousov, Y. Yao, Altermagnetism: Exploring New Frontiers in Magnetism and Spintronics. Adv. Funct. Mater. 2024, 34, 2409327. https://doi.org/10.1002/adfm.202409327

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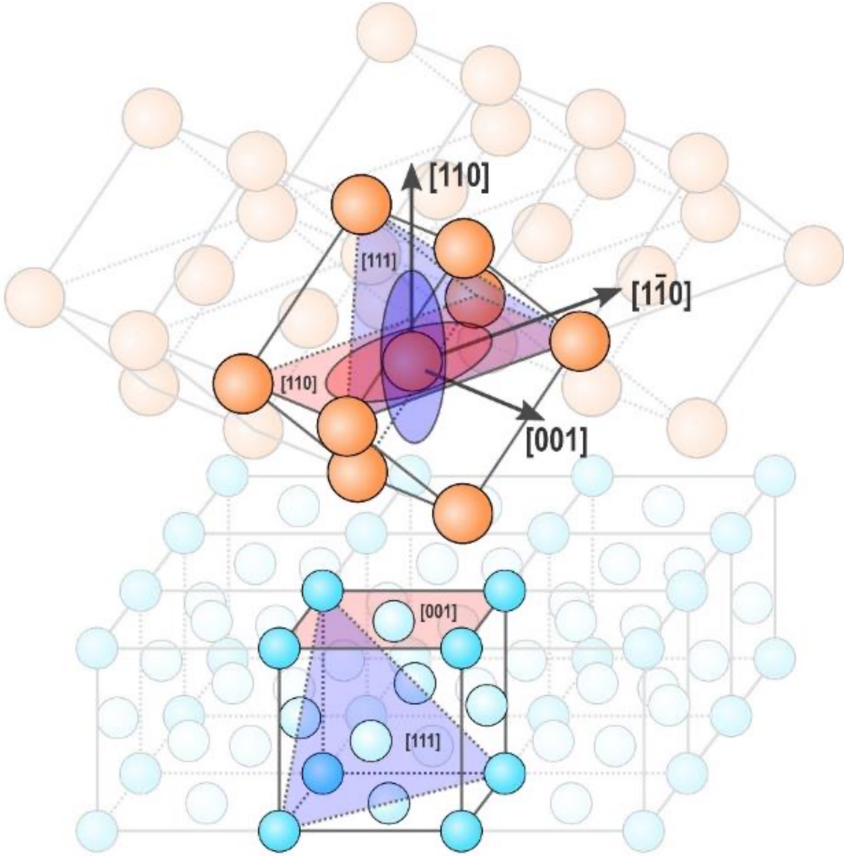
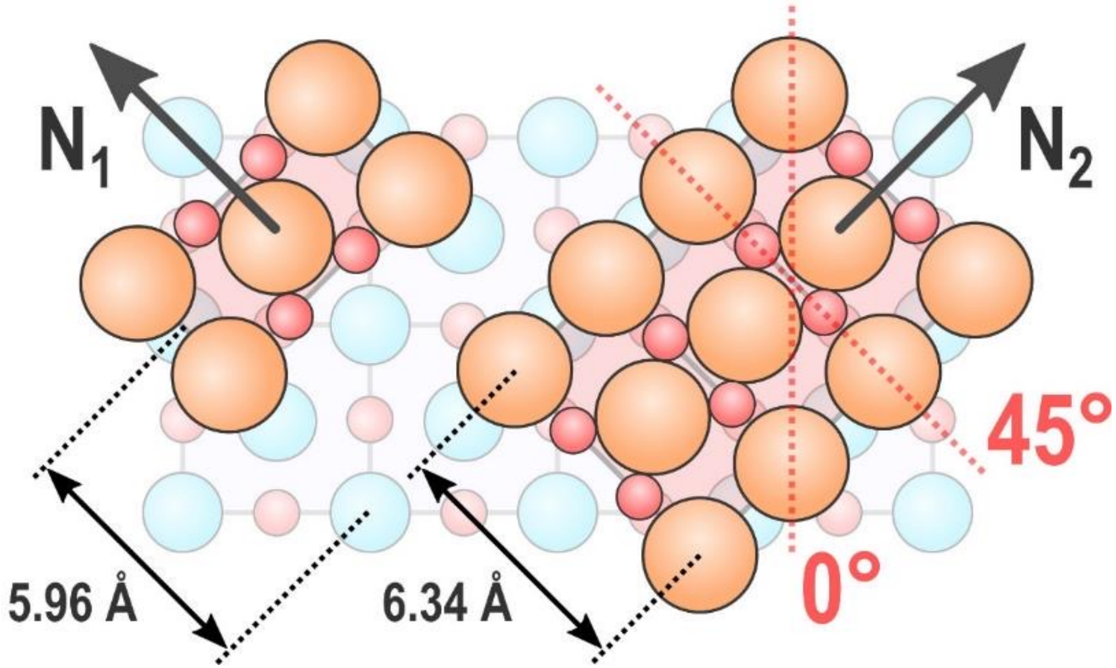
Altermagnet growth: RuO_2 on MgO (100)

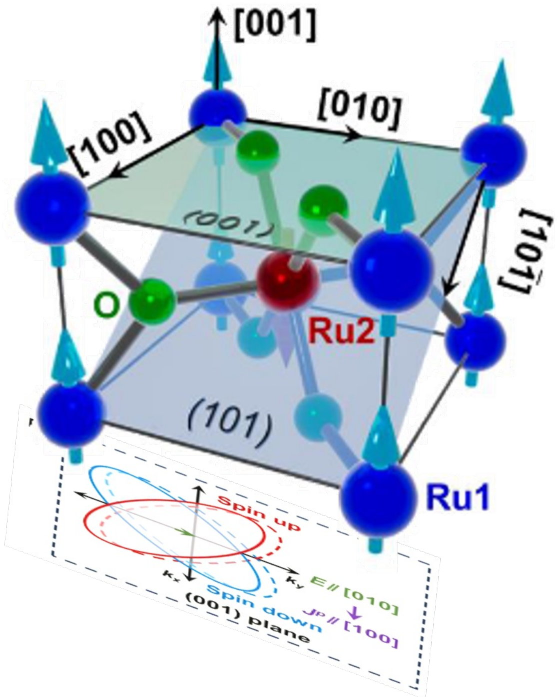


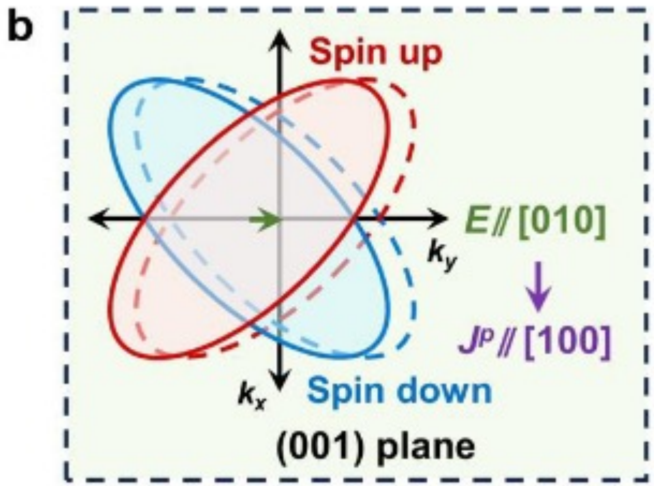


→ RuO_2 in (110) direction

→ Twinning possible

RuO_2 – Special features





→ **Need to grow (110) or (101) direction**

→ **Not many substrates possible**

→ **MgO with (001) , (110) ..**

→ **TiO_2 (100), (110) ..**

→ **MgF_2 ...**

H. Chen et al., Altermagnetic Spin-Splitting Magnetoresistance, arXiv:2412.18220 [cond-mat.mes-hall]

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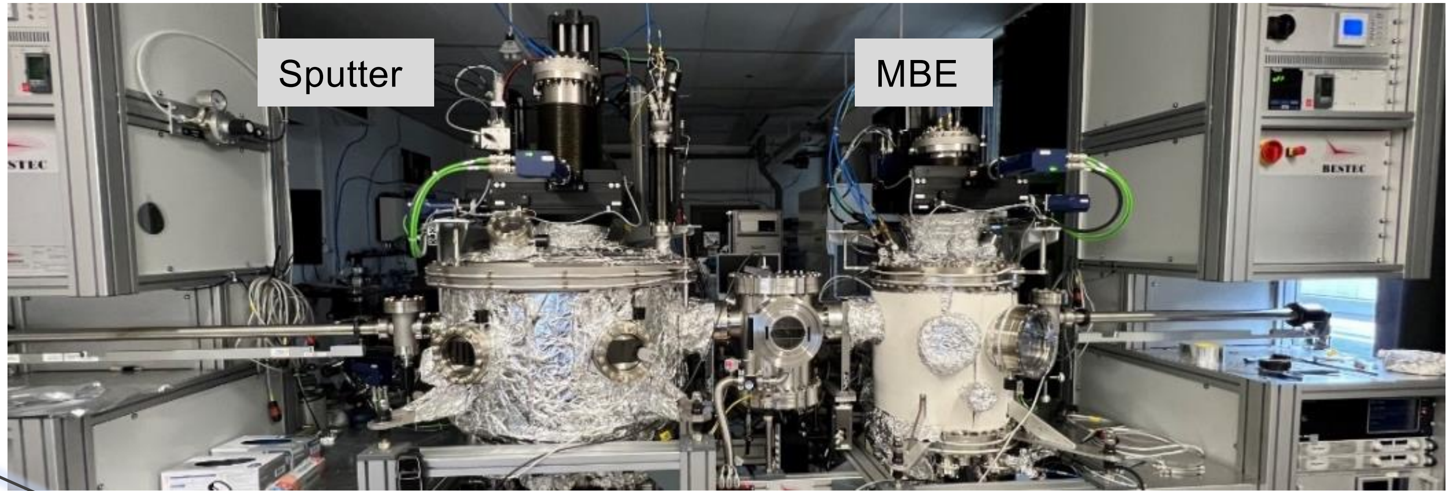
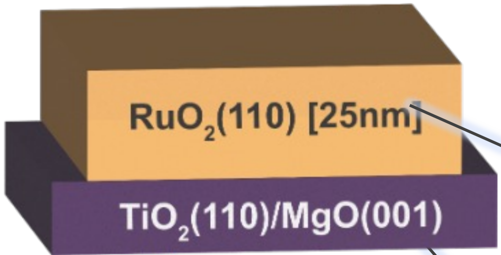
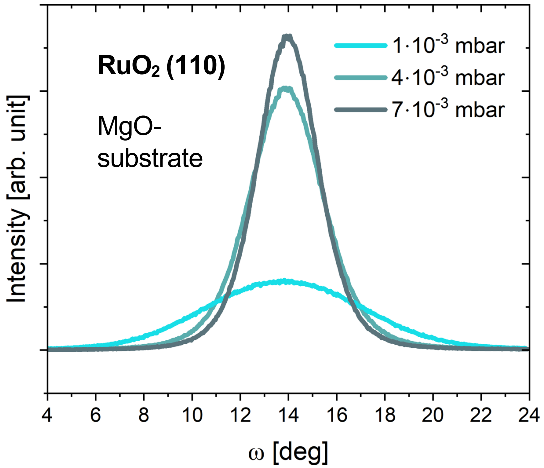
Layer deposition using magnetron sputtering

Maik Gärner







RuO_2 growth using reactive magnetron sputtering

- deposition of RuO_2 at 310°C
- Ar:O_2 ratio of 4:1
- pressure of $7 \cdot 10^{-3}$ mbar

reported techniques for single crystalline RuO_2 growth:

pulsed laser deposition: Fedchenko et al., Sci. Adv. **10**, 5 (2024)
Feng et al., Nat Electron **5**, 735 (2022)
Keßler et al., APL Mater. 12, 101110 (2024)

molecular beam epitaxy: Ruf et al., Nat Commun **12**, 59 (2021)
Bose et al., Nat Electron **5**, 267 (2022)

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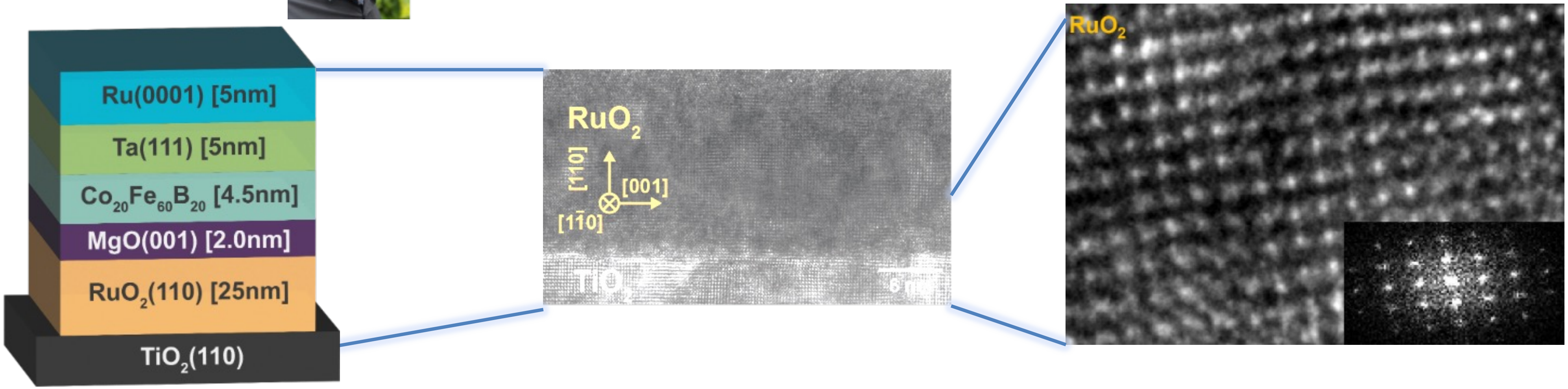
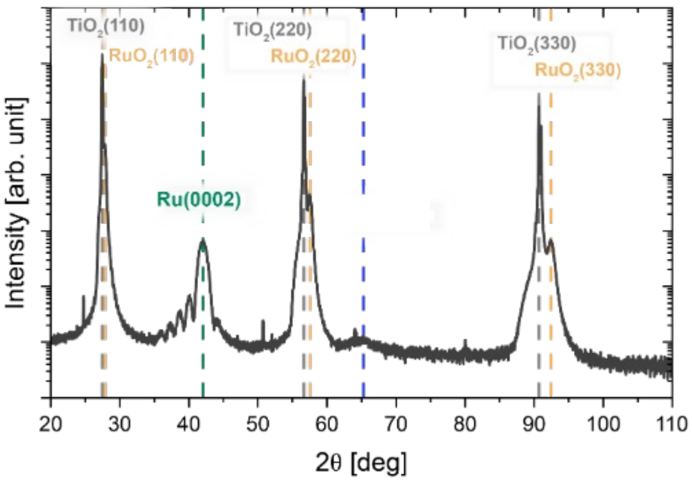
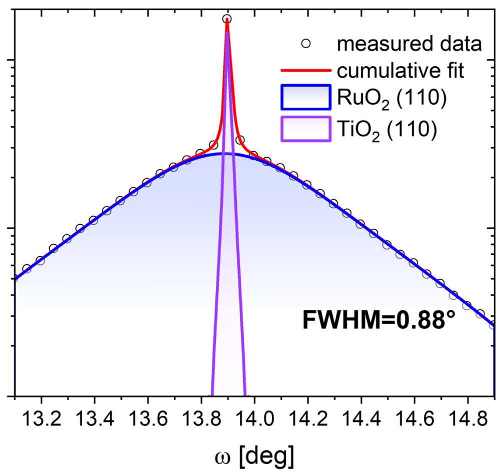
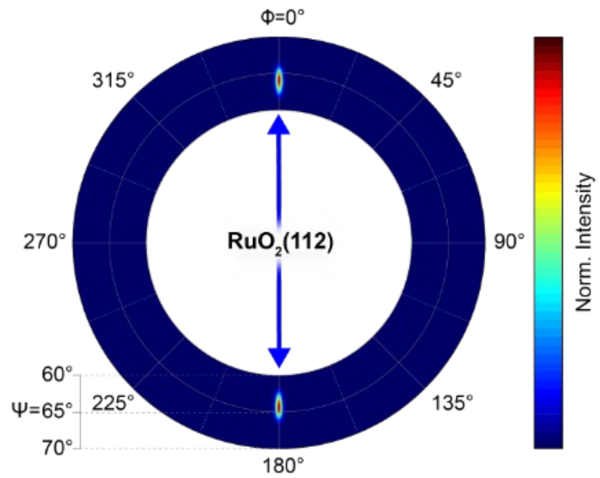
RuO_2 on TiO_2









Highly textured (110) growth of RuO_2, no twinning visible

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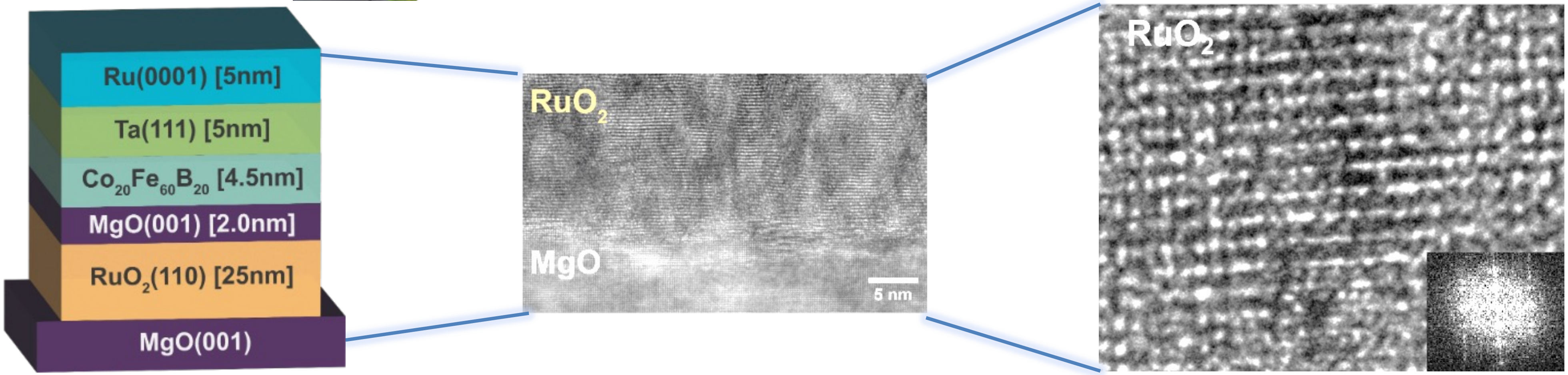
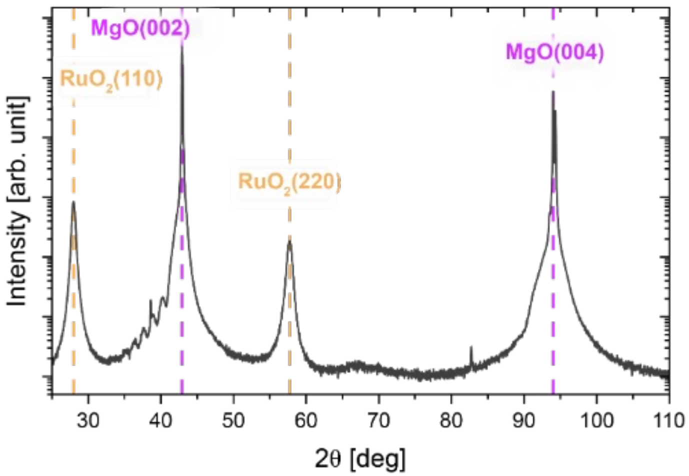
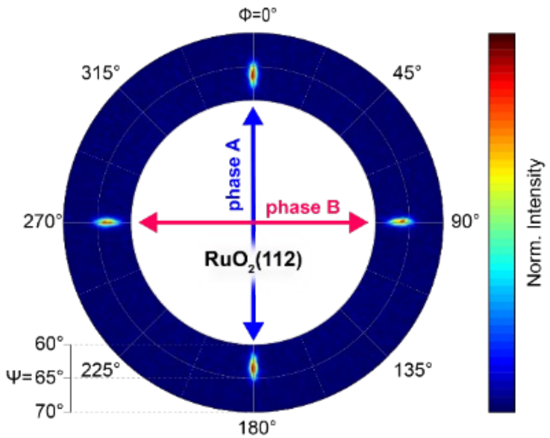
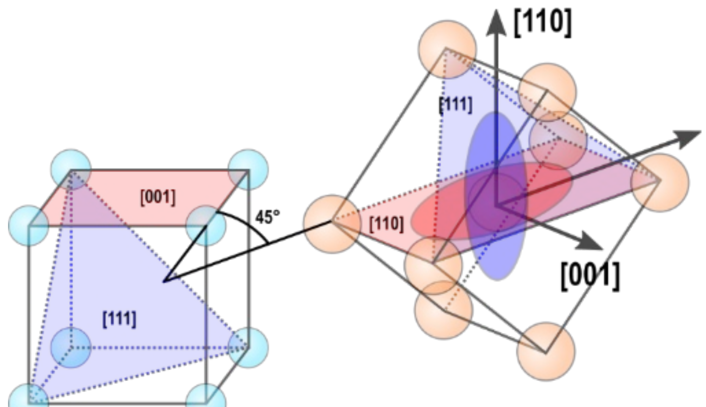
Twinned RuO_2 on MgO









Again, highly textured (110) growth of RuO_2 with twinning

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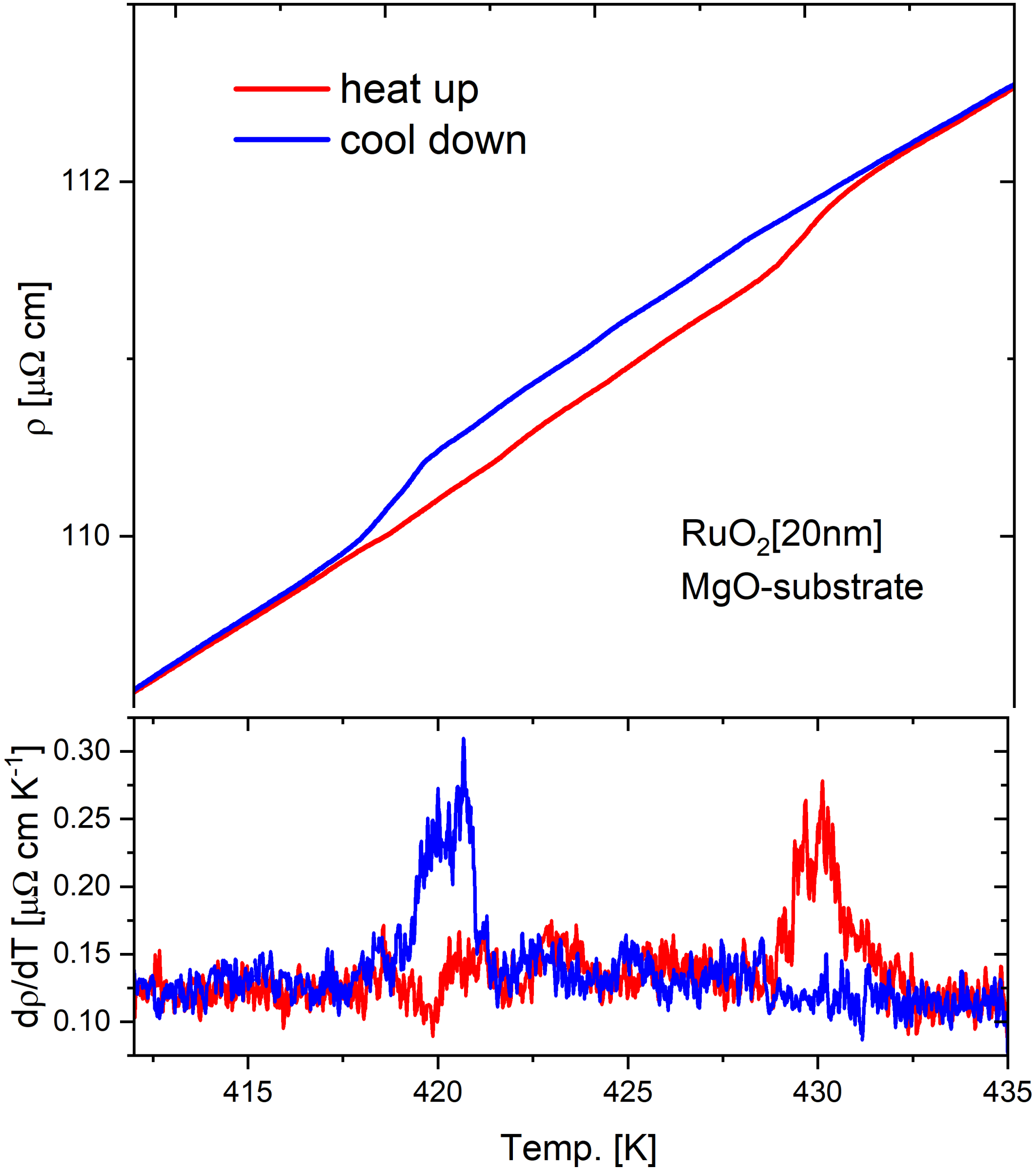
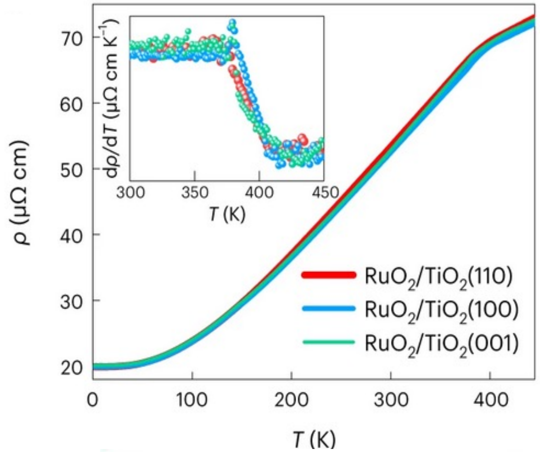
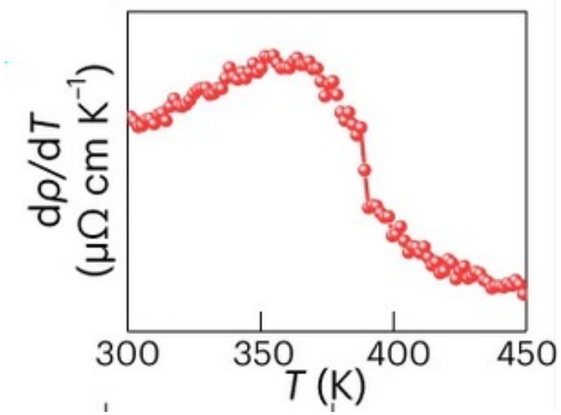
RuO_2 resistance vs. temperature





Compare to Feng et al. RuO_2/TiO_2



Feng et al. RuO_2/MgO

Similar features as in Feng et al. Nat Electron 5, 735 (2022), related with Neél temperature, but hysteretic.

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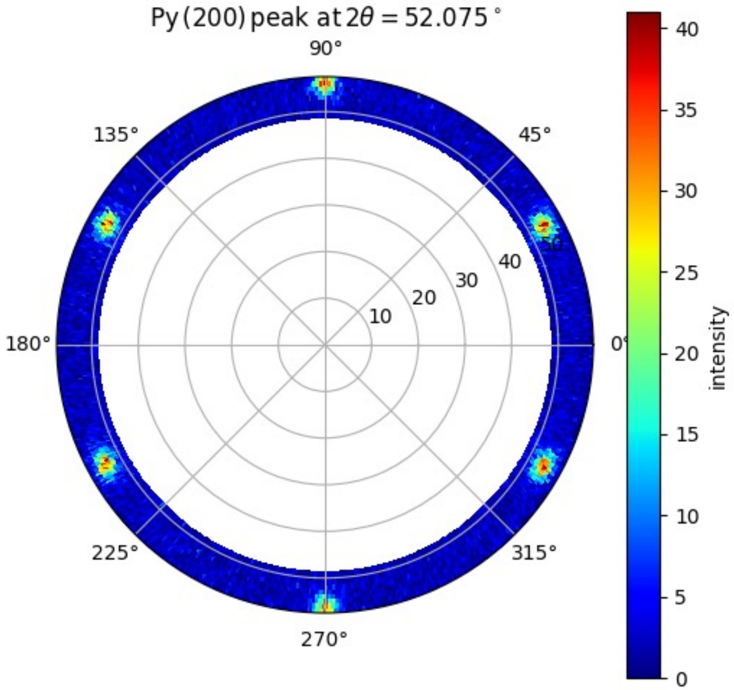
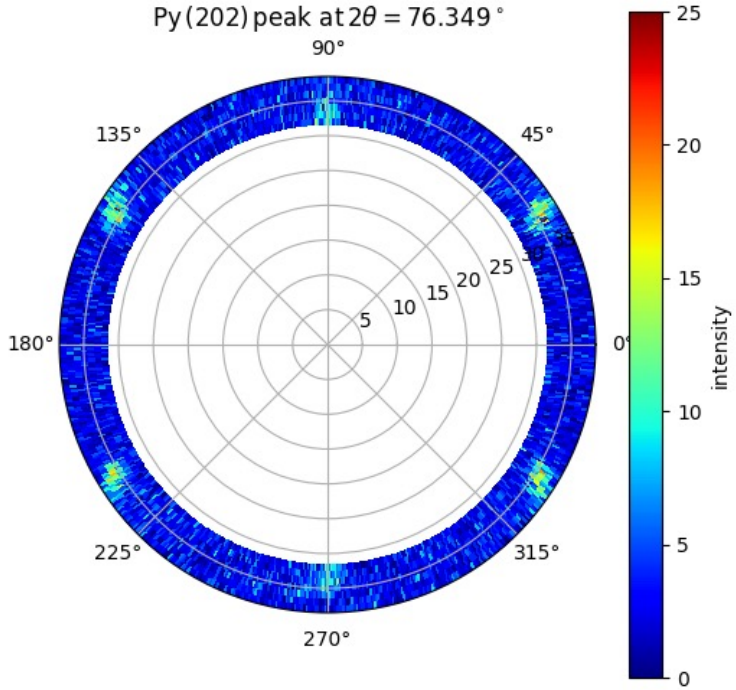
Structure of MgF_2/RuO_2/Permalloy





→ Polycrystalline growth of Permalloy ($Ni_{80}Fe_{20}$)

→ Sixfold symmetry in XRD texture maps

→ (111) texture with twinning

→ No magnetic crystalline anisotropy for Permalloy expected

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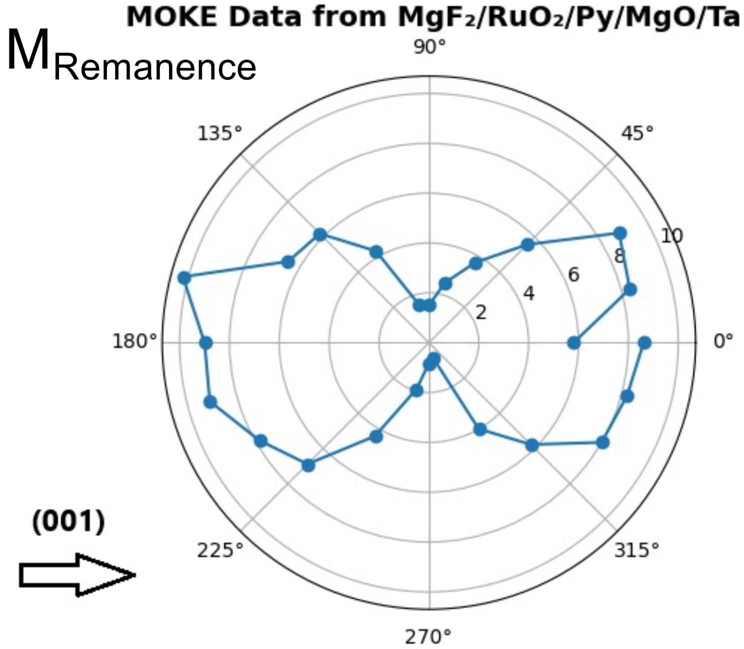
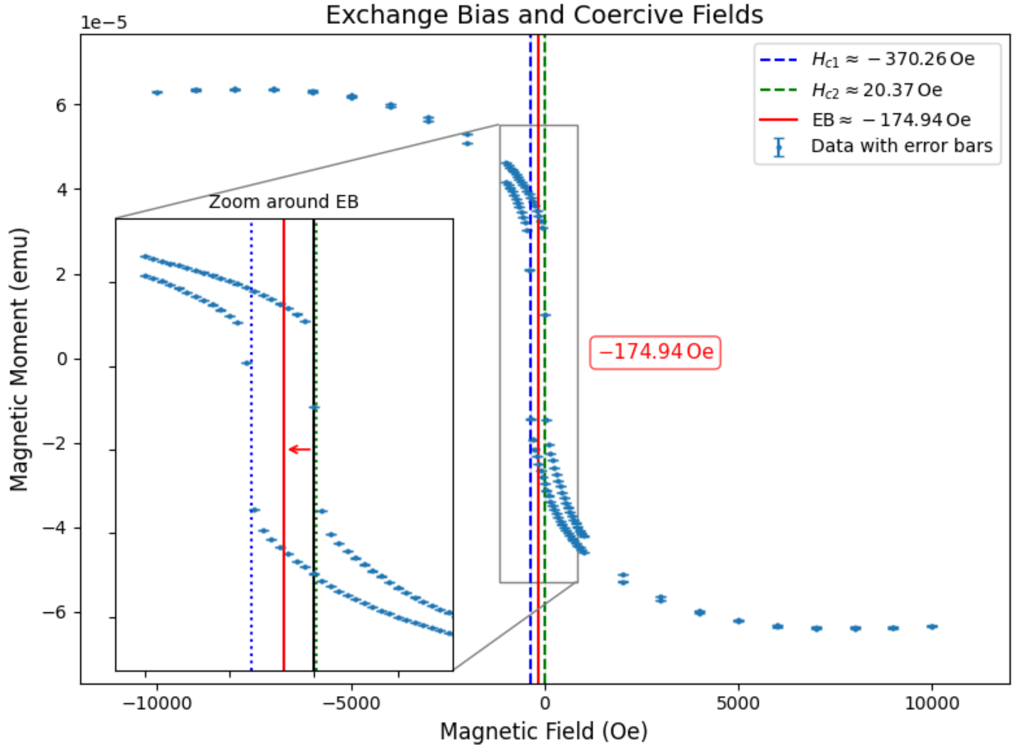
Magnetism of MgF_2/RuO_2/Permalloy





→ **Strong induced uniaxial anisotropy**

→ **Remanence different for 0° and 180° ??**

→ **Exchange bias of ≈ 17.5 mT**

→ **Hint for antiferromagnetism in RuO_2**

→ **Unstable upon annealing**

→ **μ_0 M_S for permalloy ≈ 1.05 T**

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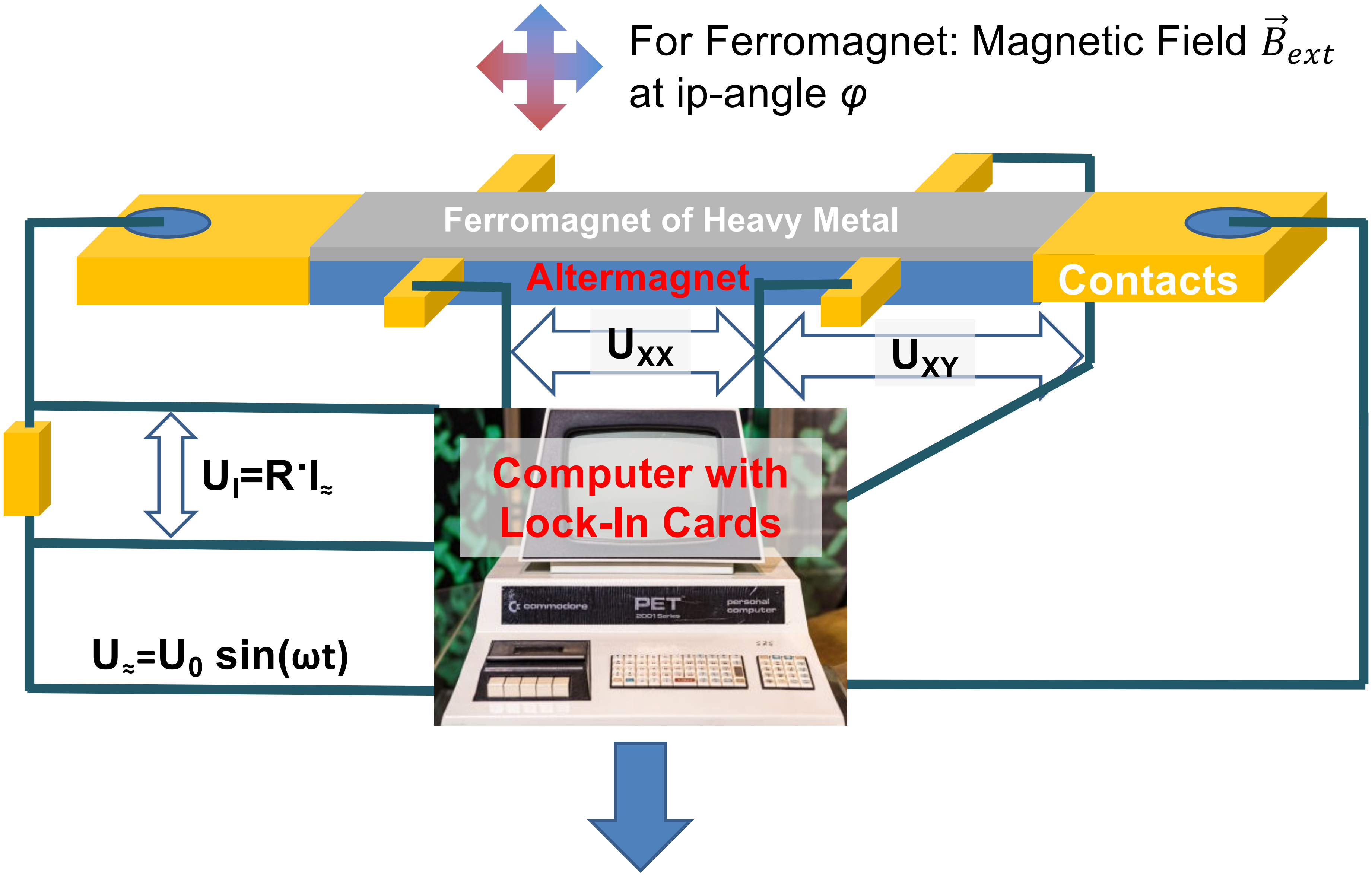
Harmonic Hall Measurements (2ω method)



First, second and third harmonic signal (x and y components)

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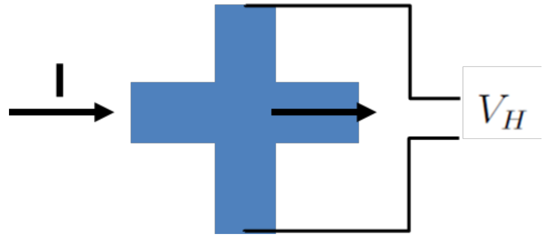
Harmonic Hall Measurements RuO_2 / Permalloy



Expect:

$$V_H = (R_H + R_{AHE}) I_0 sin(\omega t) + R^{2\omega}_{AHE} I_0 cos(2\omega t) = V_0 + V_\omega sin(\omega t) + V_{2\omega} cos(2\omega t)$$

$$V_\omega = R_P sin(2\varphi) I_0$$

R_P: Planar Hall Effect Resistance

$$V_{2\omega} = \left(-\frac{B_{FL}}{B_{ext}} R_P cos(2\varphi) - \frac{1}{2}\frac{B_{DL}}{B_{eff}} R_{AHE} + \alpha' I_0\right) \frac{I_0}{\sqrt{2}} cos(\varphi)$$

B_{FL} / B_{DL}: Field- and damping-like field
B_{eff}: Effective field including anisotropy
B_{ext}: External field
R_{AHE}: Anomalous Hall Effect Resistance
α‘ : Includes Anomalous Nernst Effect

$$\theta_{SH_{DL/FL}} = \frac{2e}{\hbar} \frac{B_{DL/FL} M_s t_{FM}}{j_{AM}\, C}$$

M_S: Saturation Magnetization
t_{FM}: Thickness of FM layer
j_{AM}: Current density in AM
c: Correction factor* ≈ 1/1.45

* L. Neumann, M. Meinert; Influence of the Hall-bar geometry on harmonic Hall voltage measurements of spin-orbit torques. *AIP Advances* 1 September 2018; 8 (9): 095320. https://doi.org/10.1063/1.5037391

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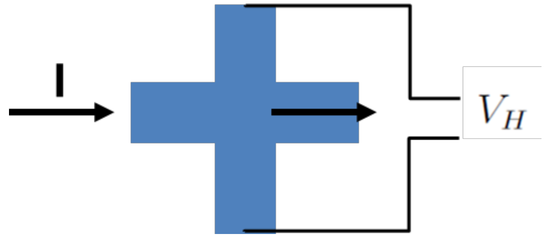
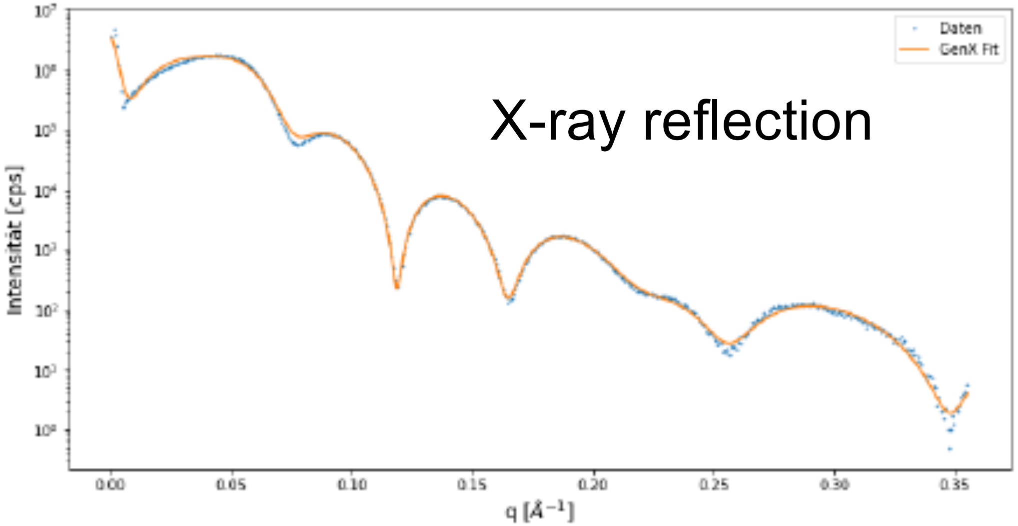
Harmonic Hall Measurements RuO_2 / Permalloy

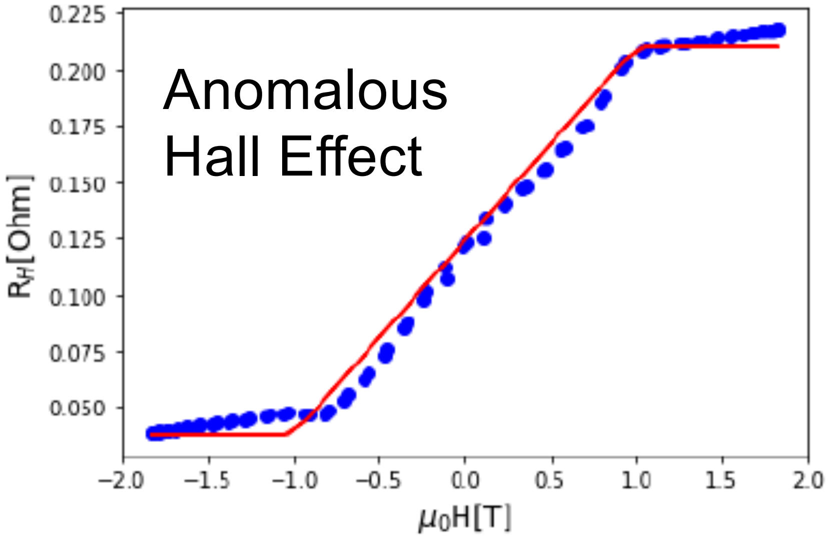




t_{FM} = 4.54 ± 0.23 nm

t_{AM} = 5.56 ± 0.6 nm

Roughness < 1nm

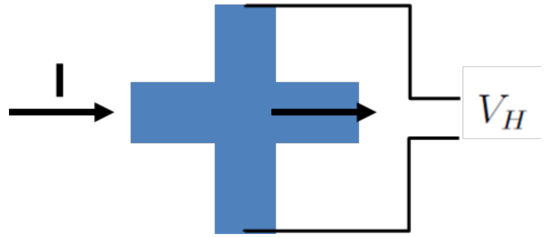


$\mu_0 M_s \approx 1 \pm 0.02$ T

$R_{AHE} = 0.086 \pm 0.001\Omega$

Harmonic Hall Measurements RuO_2 / Permalloy

Niklas Schmolka

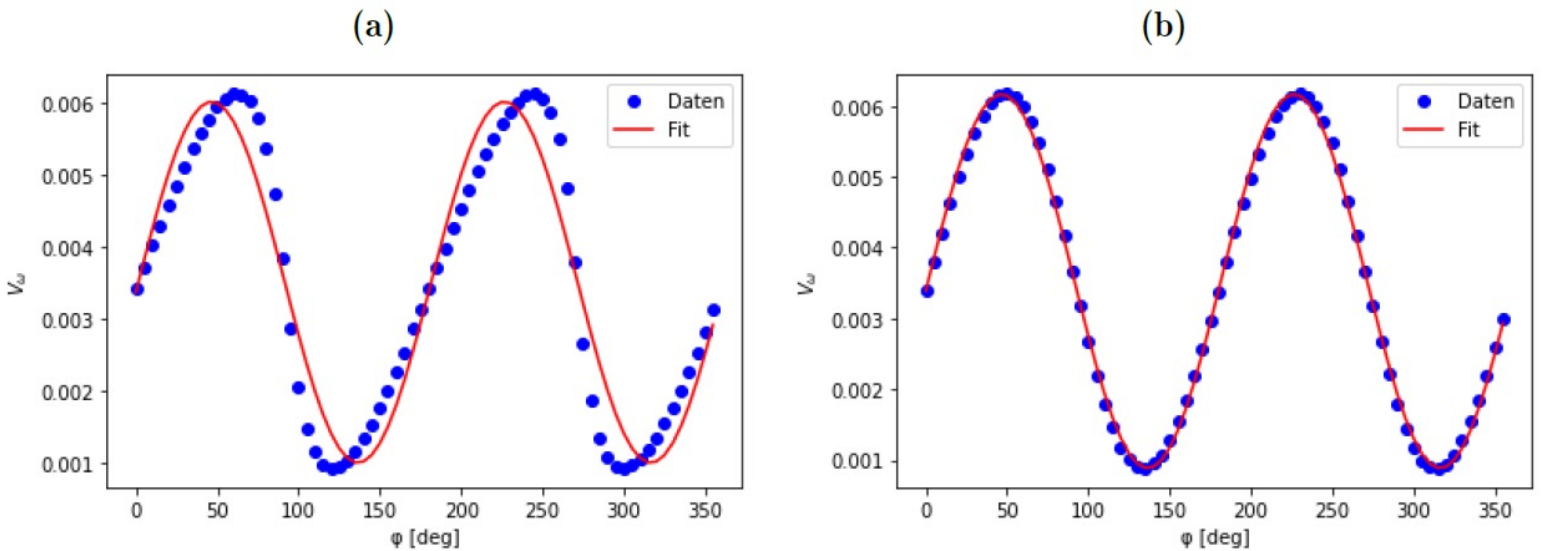


Expect:

$$V_\omega = R_P sin(2\varphi) I_0$$ **„Planar Hall Effect“**

$$V_{2\omega} = (-\frac{B_{FL}}{B_{ext}} R_P cos(2\varphi) - \frac{1}{2}\frac{B_{DL}}{B_{eff}} R_{AHE} + \alpha' I_0)\frac{I_0}{\sqrt{2}} cos(\varphi)$$

Get:



Examples of the first harmonics for a magnetic field of (a) $\mu_0 H$ = 80mT and (b) $\mu_0 H$ = 350mT.

Harmonic Hall Measurements RuO_2 / Permalloy

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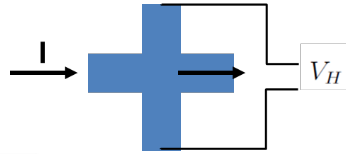
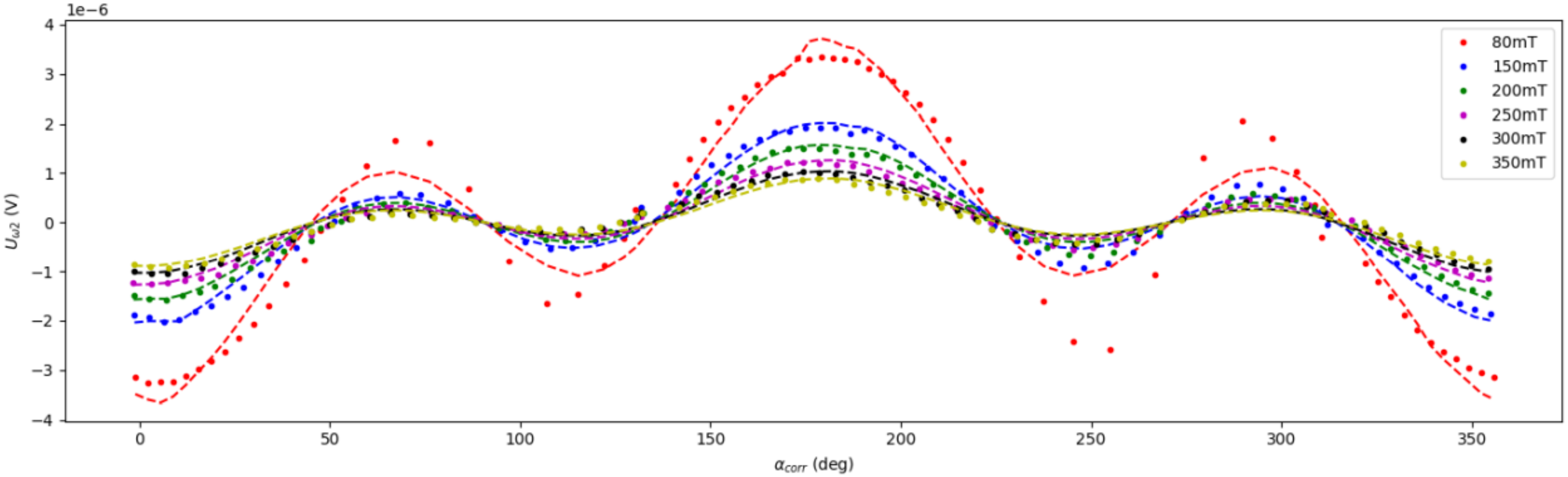
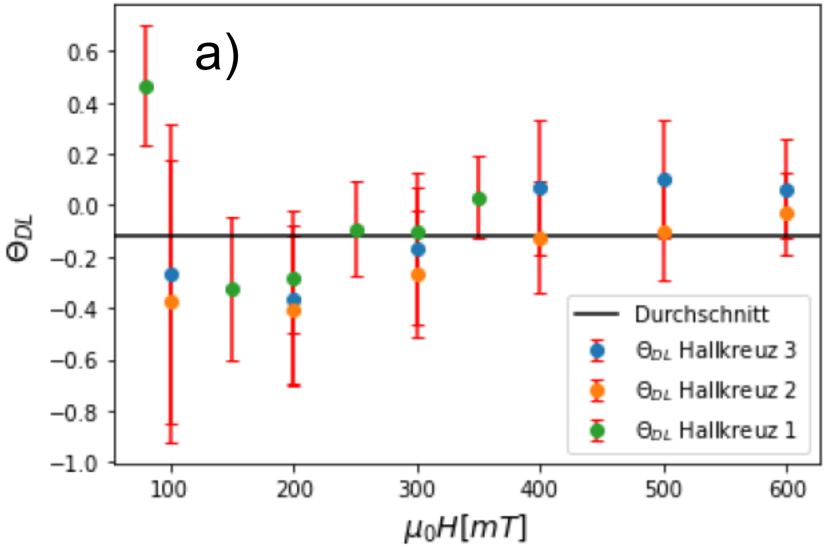
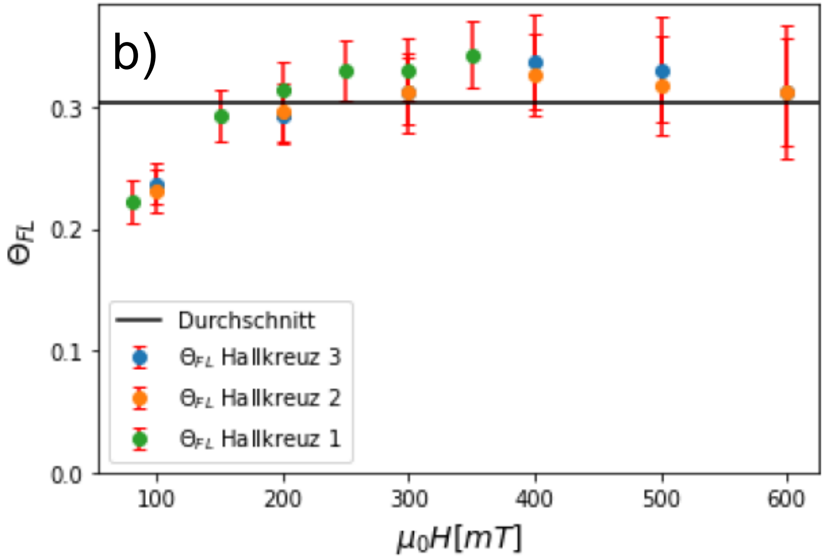




Second harmonic Hall Voltage for different applied fields





The (a) damping-like θ_{SHDL} and (b) field-like θ_{SHFL} SHA's of the Hall crosses at different applied fields → Torques seem to be present → Antiferromagnetism

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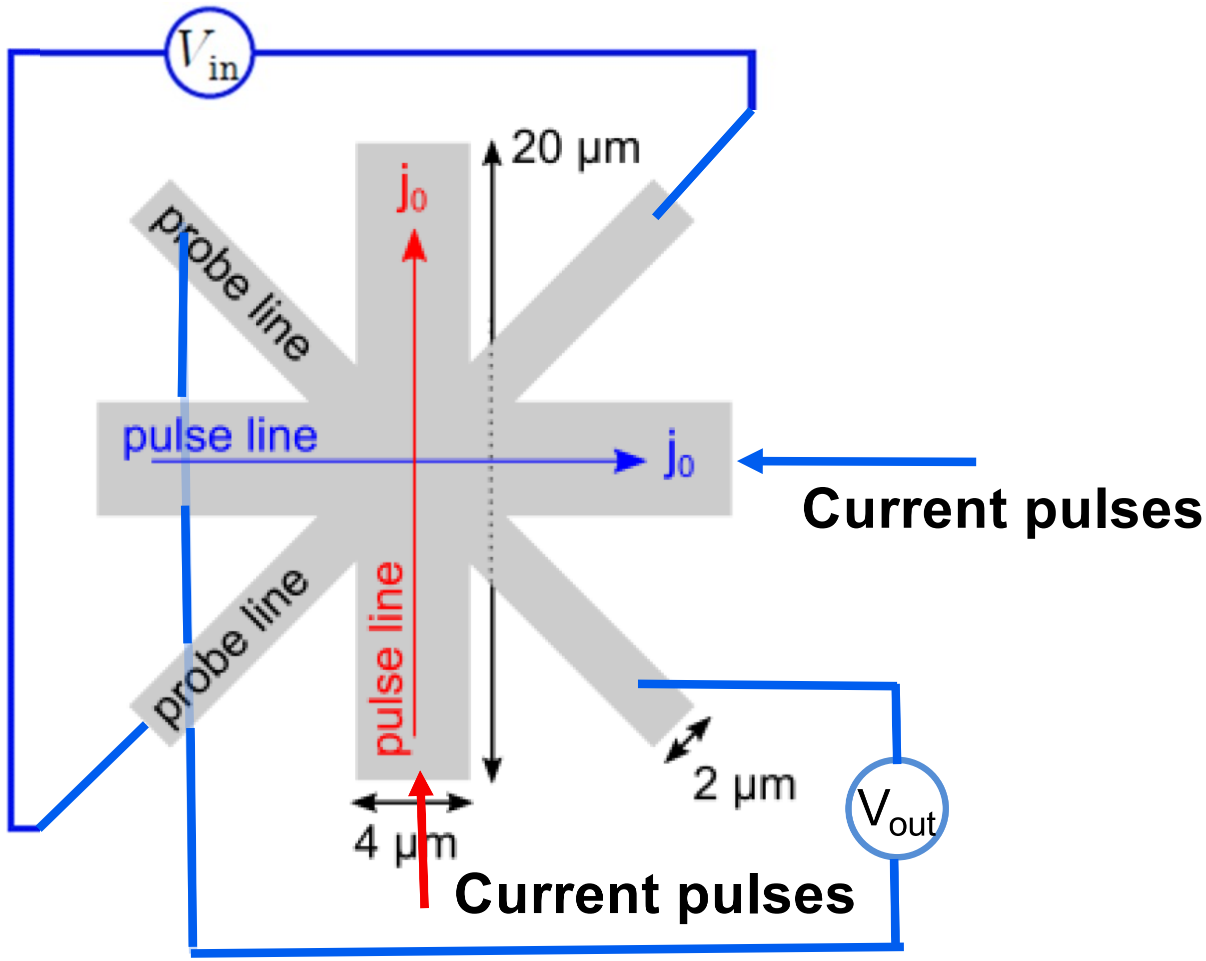
Neél vector switching in RuO_2/Pt

Florian Knossalla

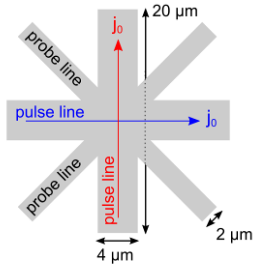
Image of the *8-cross pattern* with an overlay depicting the measurement geometry.

Detect either longitudinal resistance (AMR) or
-as in the sketch-
perpendicular voltage (PHE).



Florian
Knossalla

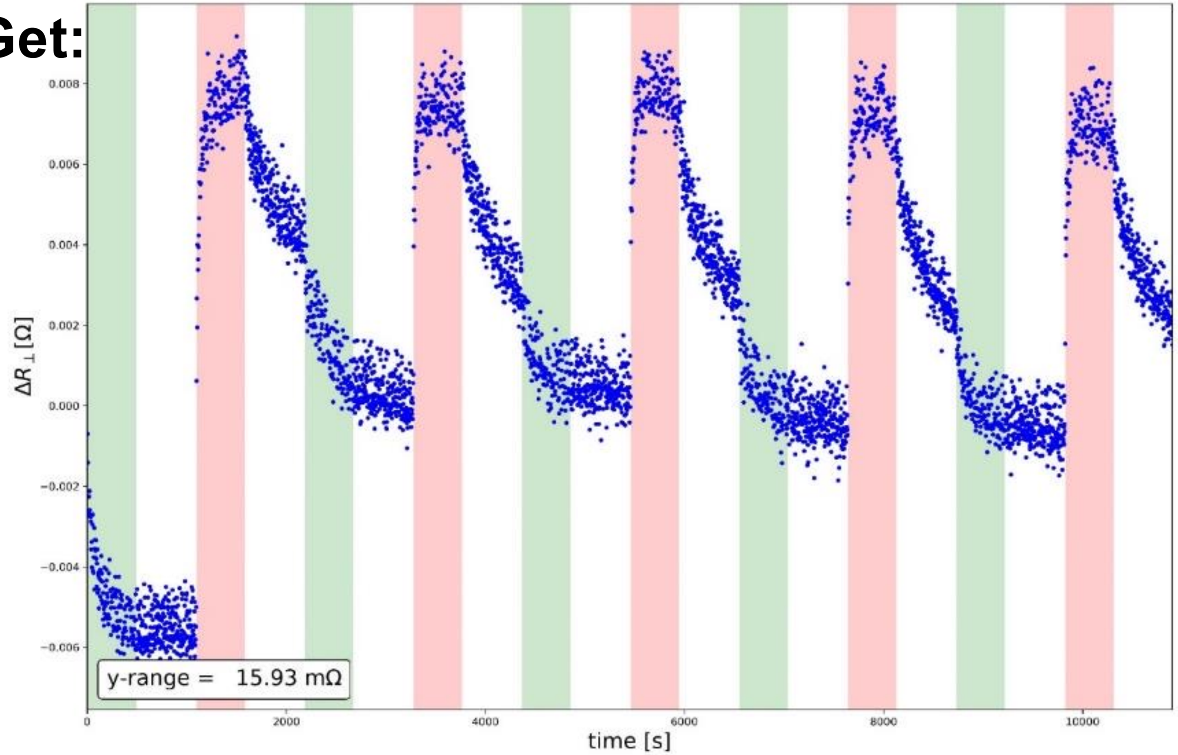
Neél vector switching in RuO_2/Pt



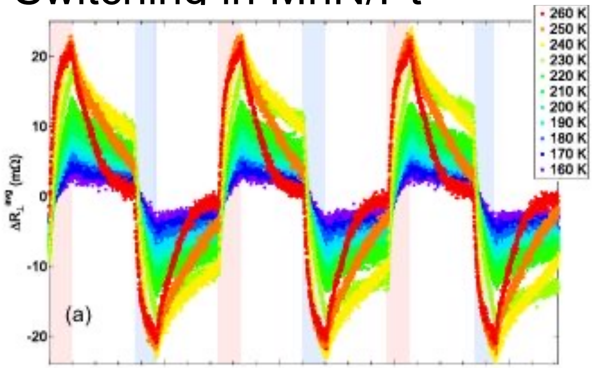
Expect:

- **Nothing if all is simply metallic and not magnetic ?**
- **Anisotropic Magnetoresistance or Planar Hall voltage, if Neél vector rotates**

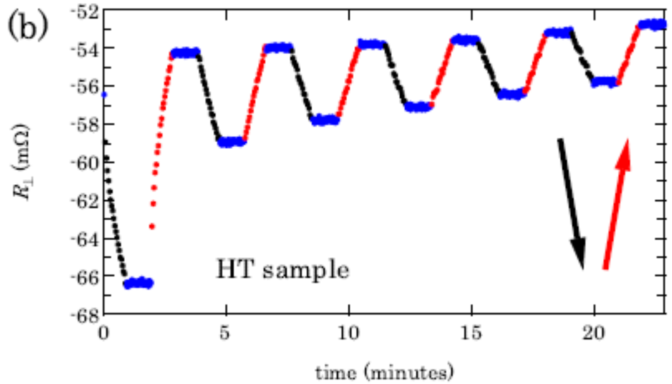
Get:



Compare to
Switching in MnN/Pt[1]



Control in Nb (Electromigration)[2]



[1] M. Dunz, PhD thesis Uni Bielefeld (2021), Prof. M. Meinert,

[2] Phys. Rev. Research, 2(3):033077, 2020
https://doi.org/10.1103/PhysRevResearch.2.033077

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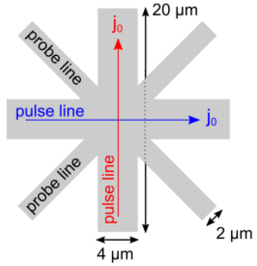
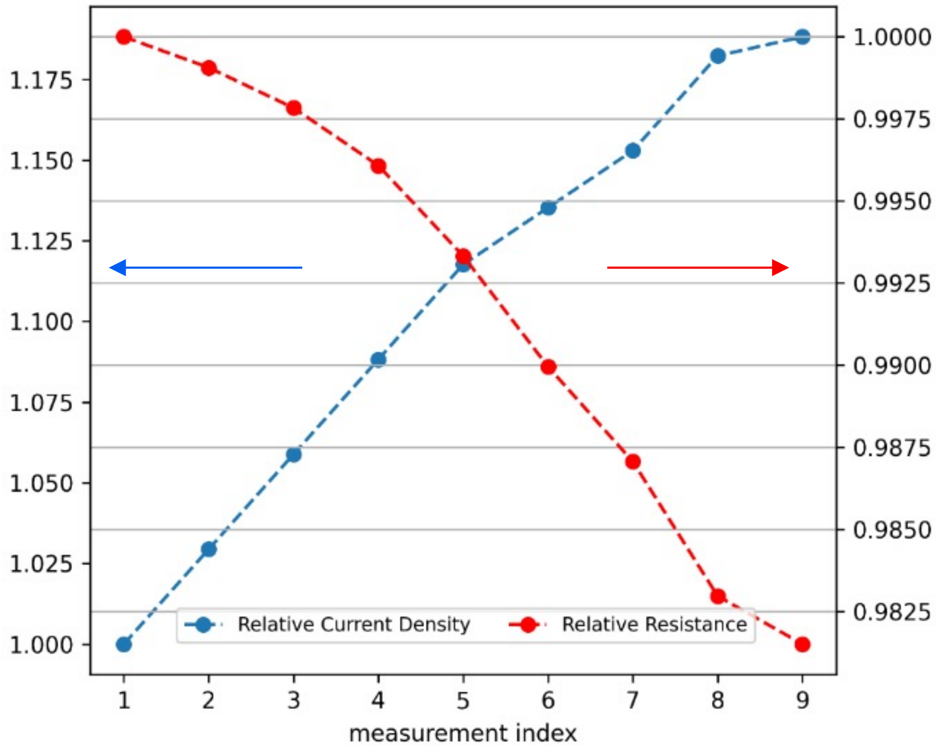
Florian Knossalla

Neél vector switching in RuO_2/Pt



Unclear up to now, if really Neél-Vector switching is achieved.

Seems, however, not to be (pure) electromigration.



Ongoing experiments:

Resistance drops upon increasing the pulse current density.

Look for structural changes…

- Introduction Heterostructures
  - New features with in situ resistance and magnetoresistance measurements
  - Sensing applications
- **Altermagnets**
  - Growth of RuO_2
  - Properties of RuO_2 / Permalloy
  - Harmonic Hall investigation of torques in RuO_2 / Permalloy
  - Neél vector switching in RuO_2/Pt
  - **Magnetic tunnel junctions RuO_2/MgO/CoFeB**
  - Growth of Mn_5Si_3
- Outlook

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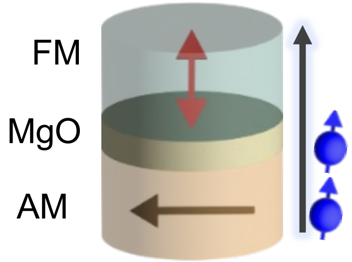
Altermagnetic tunneling magnetoresistance

Maik Gärner

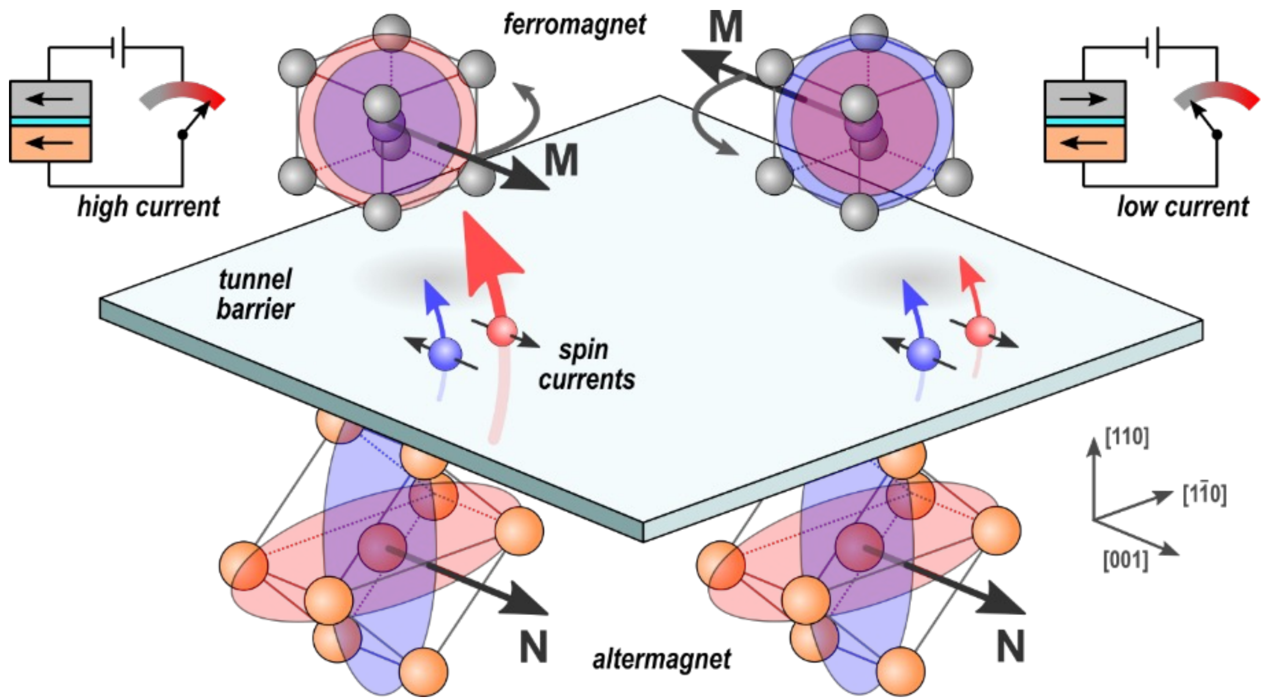


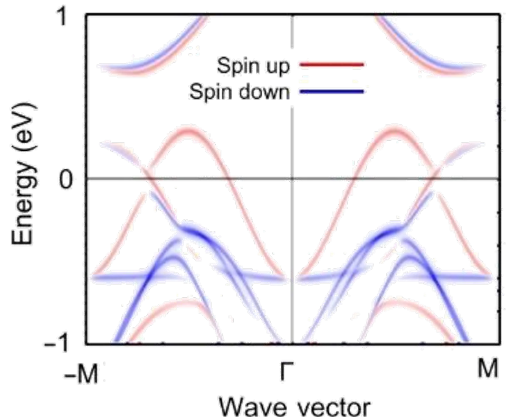
RuO_2 (110)/barrier/ferromagnet tunnel junction

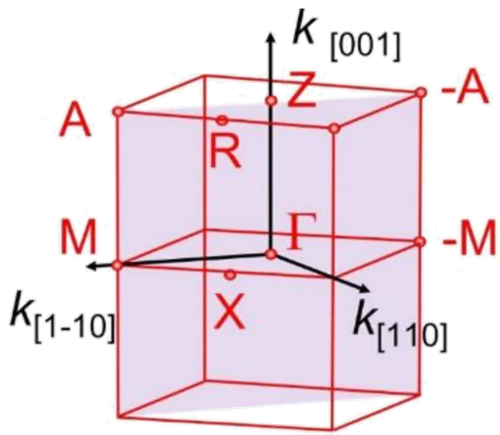
RuO_2 spin splitting along Γ-M ([110]) direction

➡ spin-polarized current along [110]

➡ different transmissions for parallel/antiparallel states







Fedchenko et al., Sci. Adv. **10**, 5 (2024)

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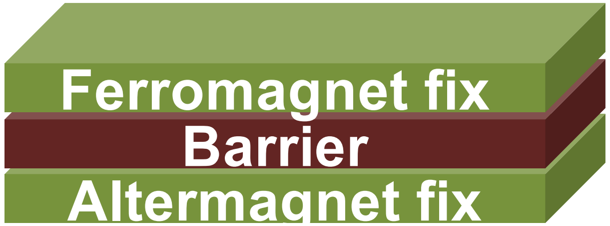
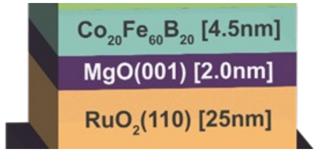
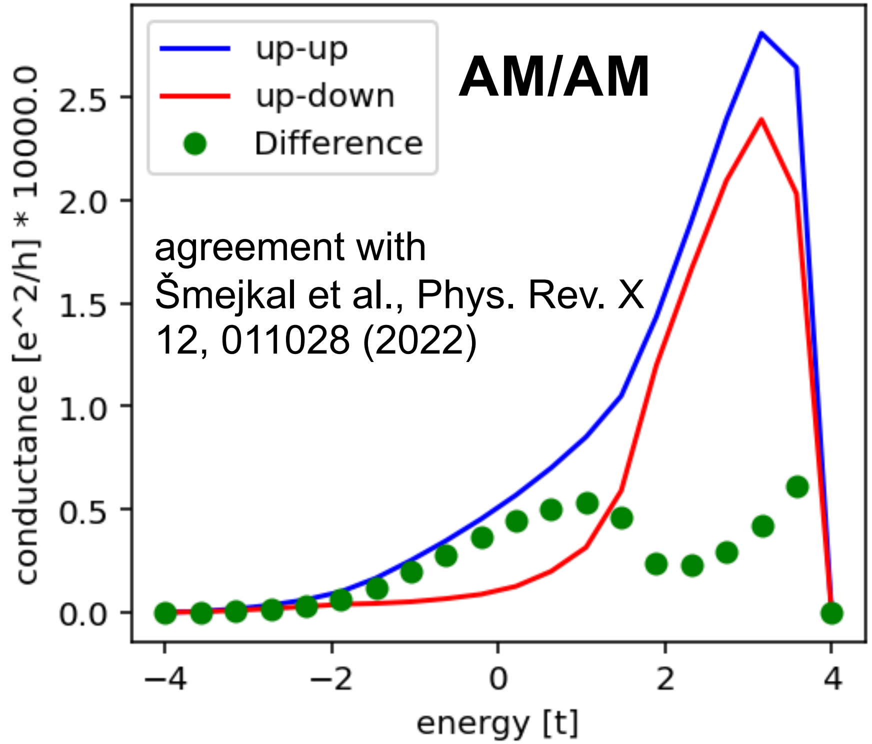
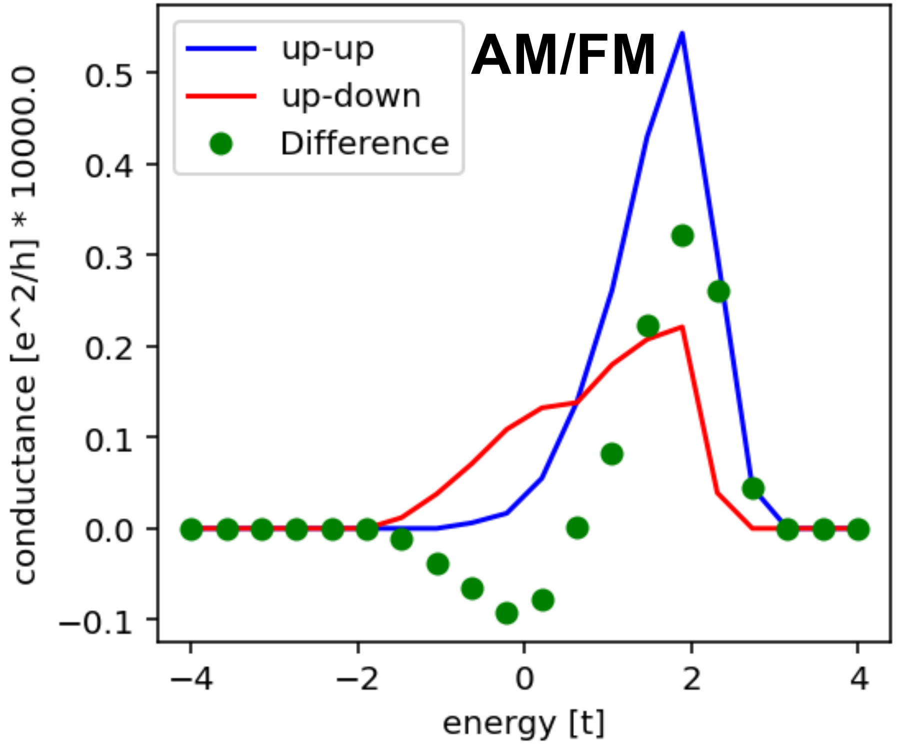
TMR RuO_2 – Ferromagnet: What to expect?



→ kwant







Different features: Smaller conductance, up-up can be also smaller than up-down

But: Energy not experimentally accessible

Accessible parameters: Voltage U, direction of $\overrightarrow{M}_{FM}$

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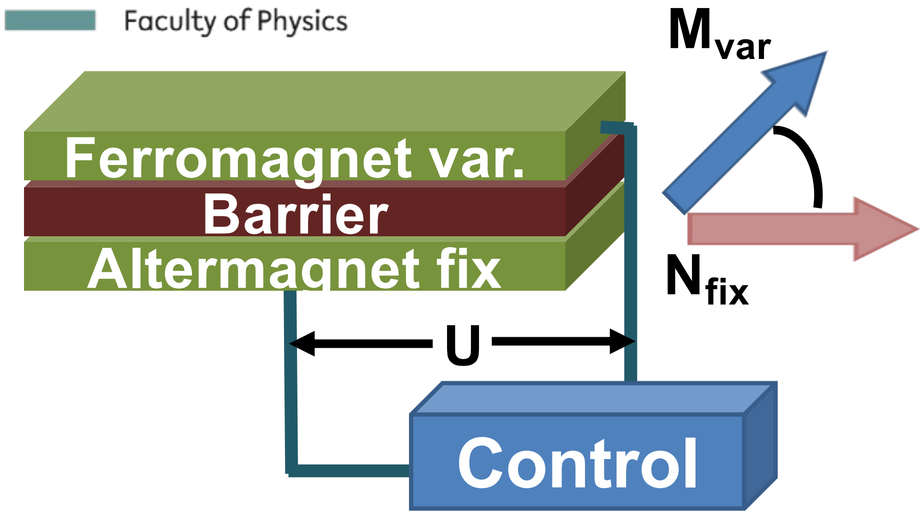
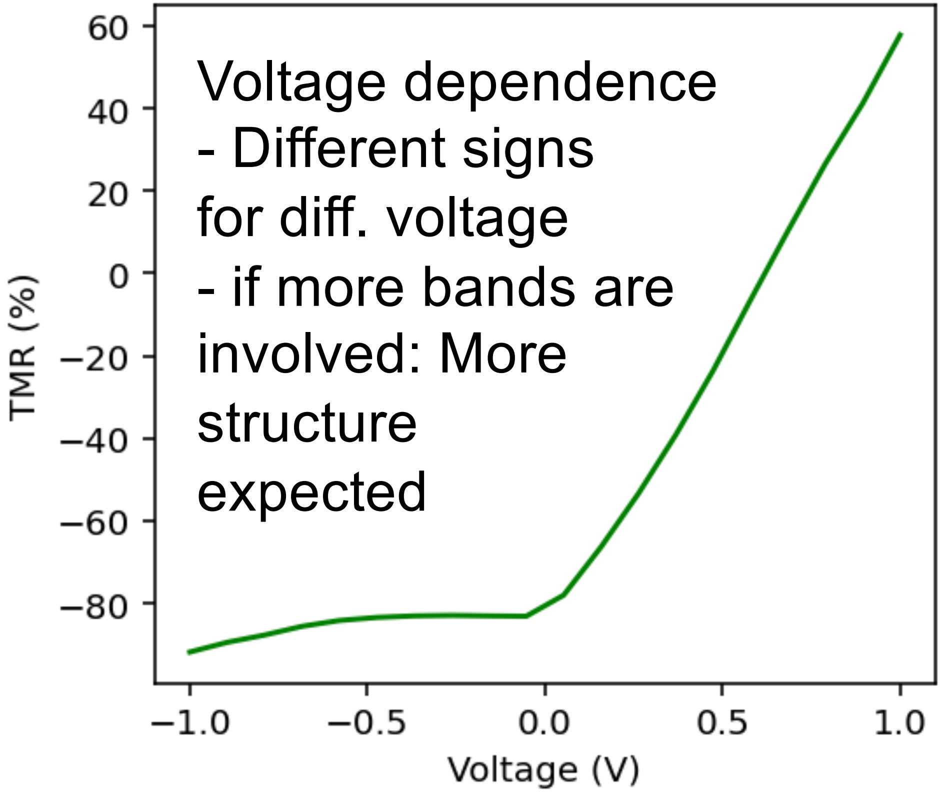
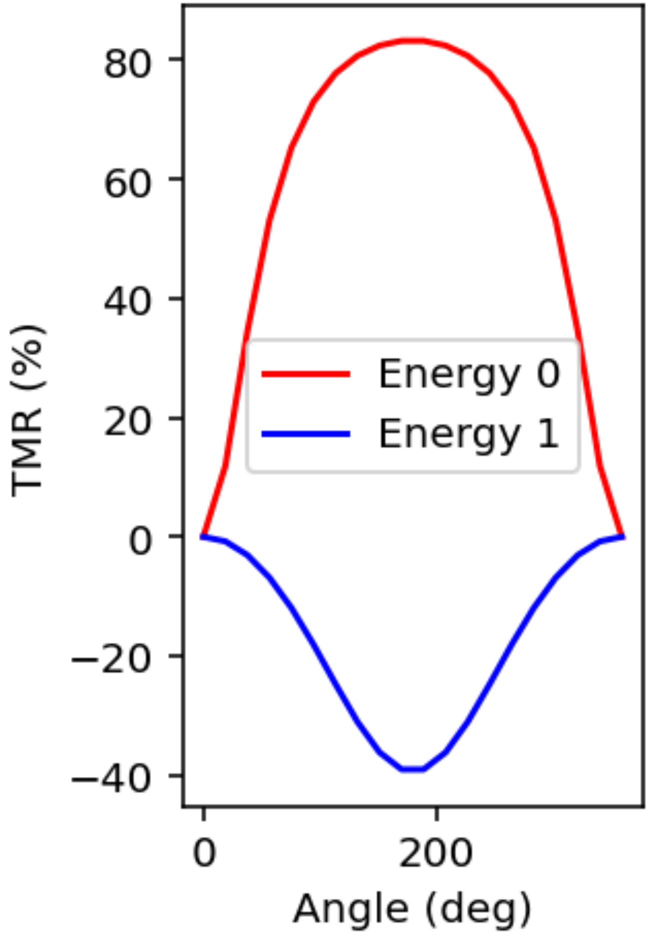
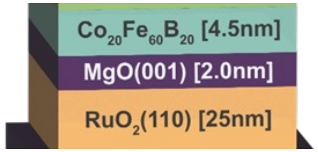
TMR RuO_2 – Ferromagnet: What to expect?





Voltage dependence
- Different signs for diff. voltage
- if more bands are involved: More structure expected





Angle dependence
- **Different signs for diff. energy**
- **not sinusoidal**

In comparison with "simple" tunnel-junctions more complicated behavior expected such as sign changes or zero-TMR regions as function of voltage.

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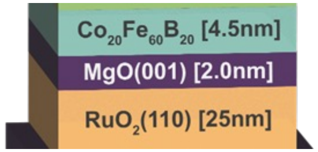
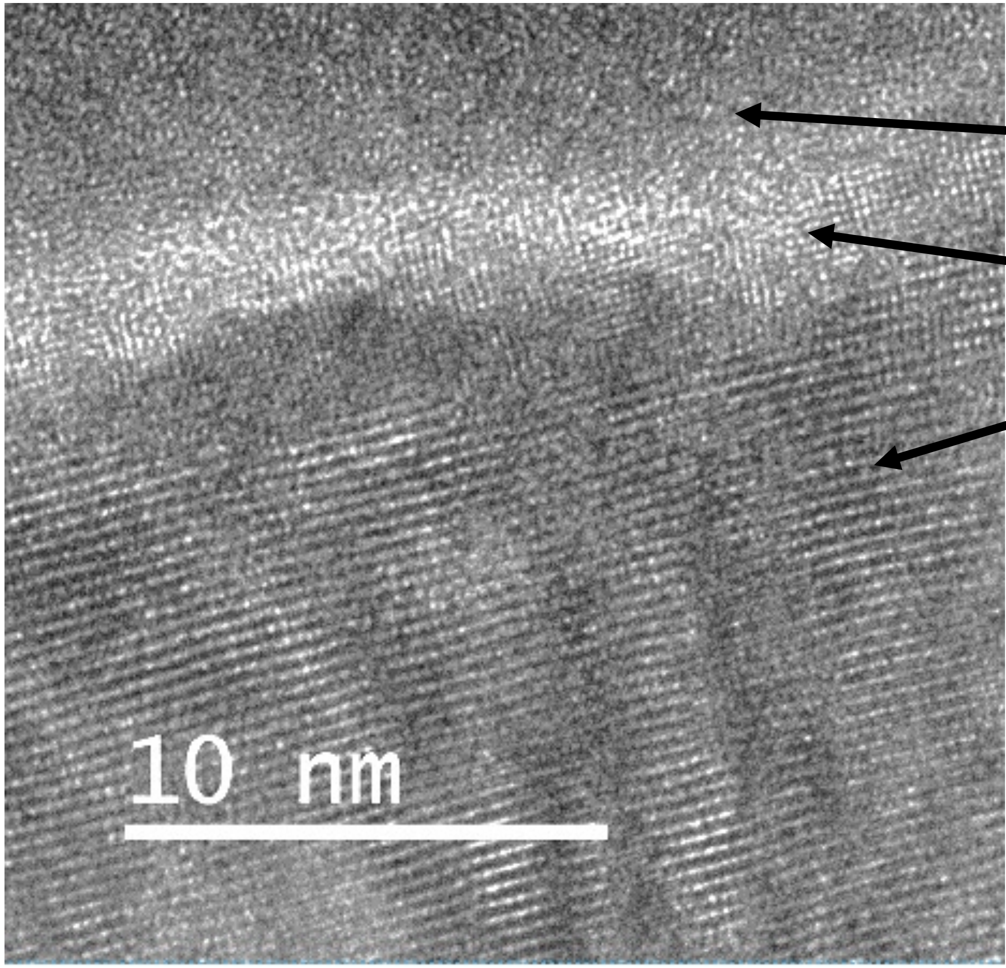
Inga Ennen

RuO_2 / MgO / CoFeB tunnel junctions



MgO/RuO2[20nm]/MgO[2.1nm]/CoFeB[4nm] – High resolution TEM



Mainly amorphous CoFeB

Partly crystalline MgO

Twinned RuO_2 (110)

- → **RuO_2 on MgO shows twinned structure**
- → **On TiO_2 much less twinning**
- → **Barrier MgO continuous but rather rough, partly crystalline, ongoing work ….**

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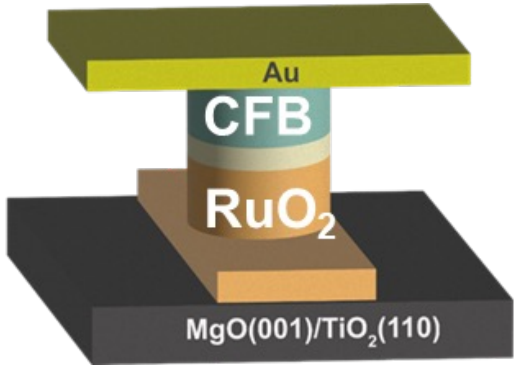
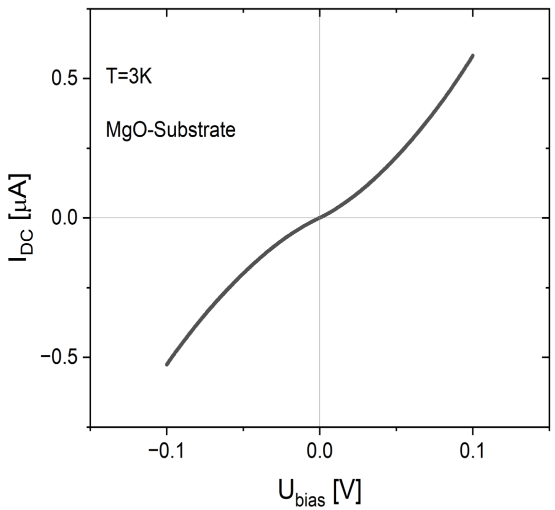
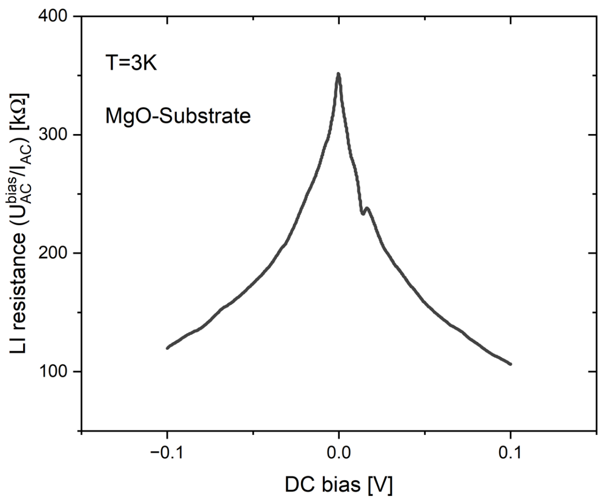
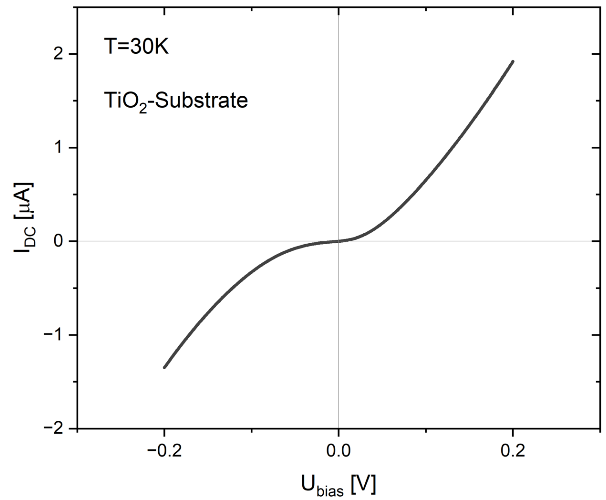


MTJ fabrication using e-beam lithography

- 3 step lithography process
- circular pillars with diameters d=$200nm$-$2\mu m$







Tunneling curves show typical nonlinear behavior around U = 0V → Tunneling seems oK.

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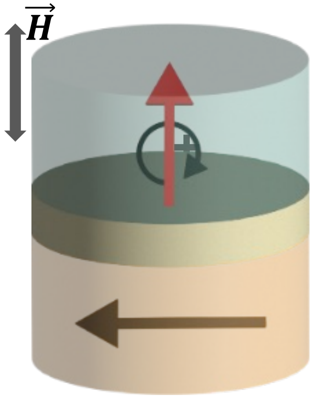
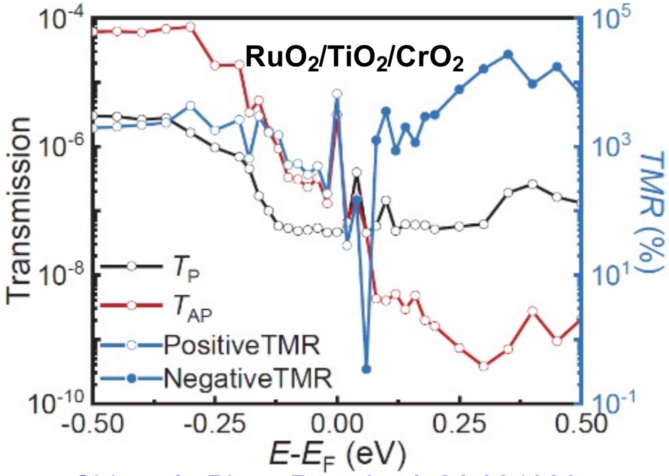
Tunneling MR in RuO_2/MgO/CoFeB
$\vec{H}$ out of plane

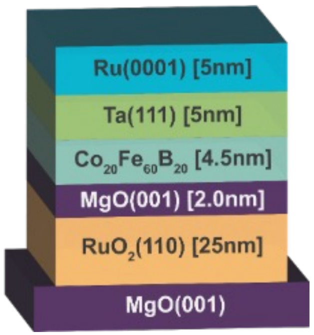


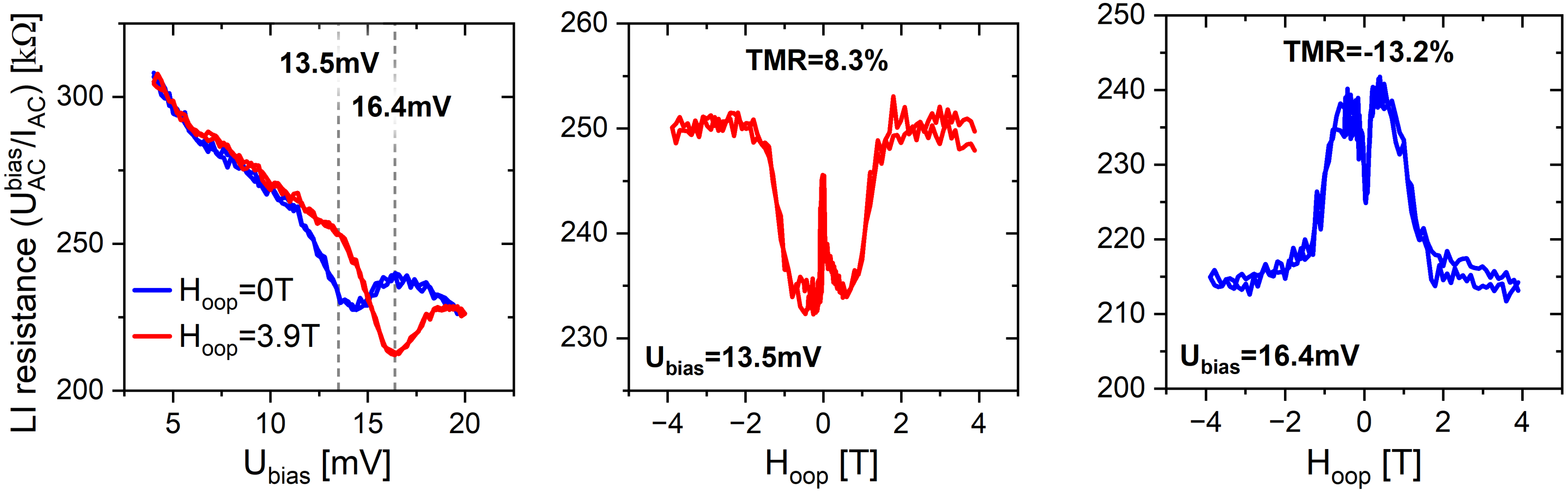
out-of-plane switching of the ferromagnet

- TMR up to 13.2% **at 3K**
- equal switching fields in TMR and VSM data
- sign of the TMR is bias voltage dependent



Chi et al., Phys. Rev. Appl. **21** 034038 (2024)





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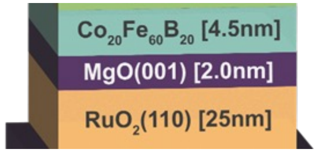
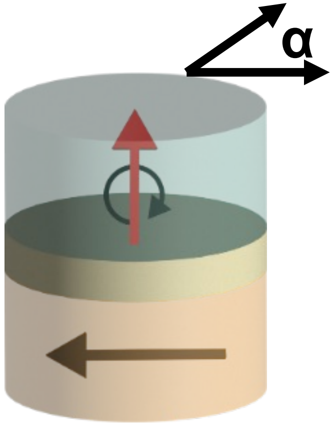
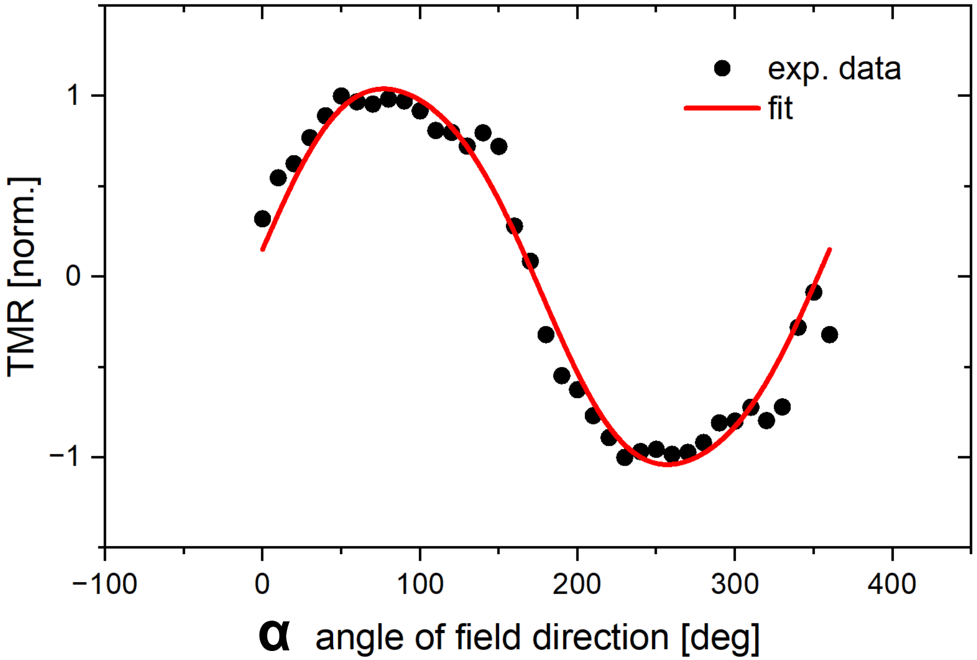
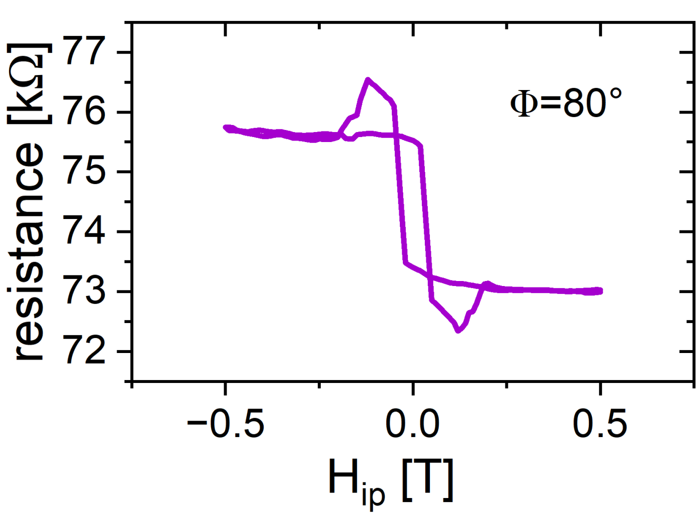
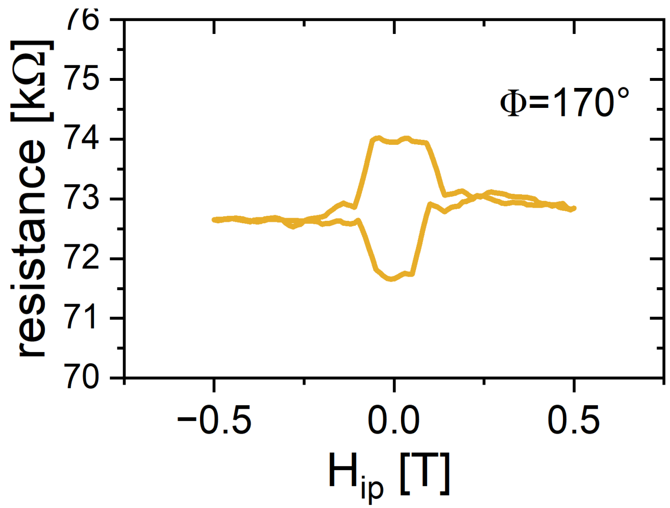
Tunneling MR in RuO_2/MgO/CoFeB
$\vec{H}$ in plane











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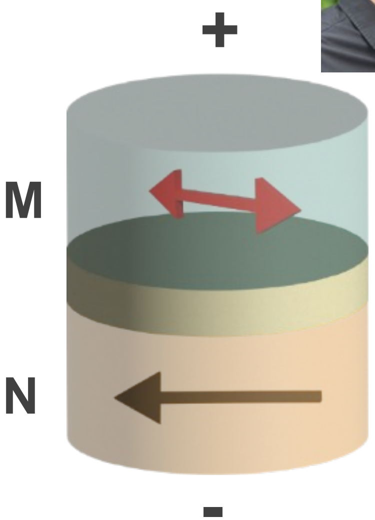
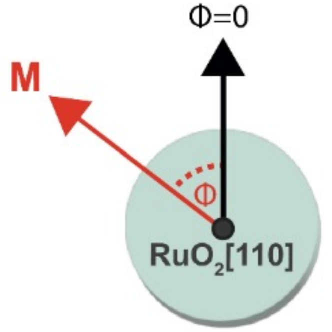
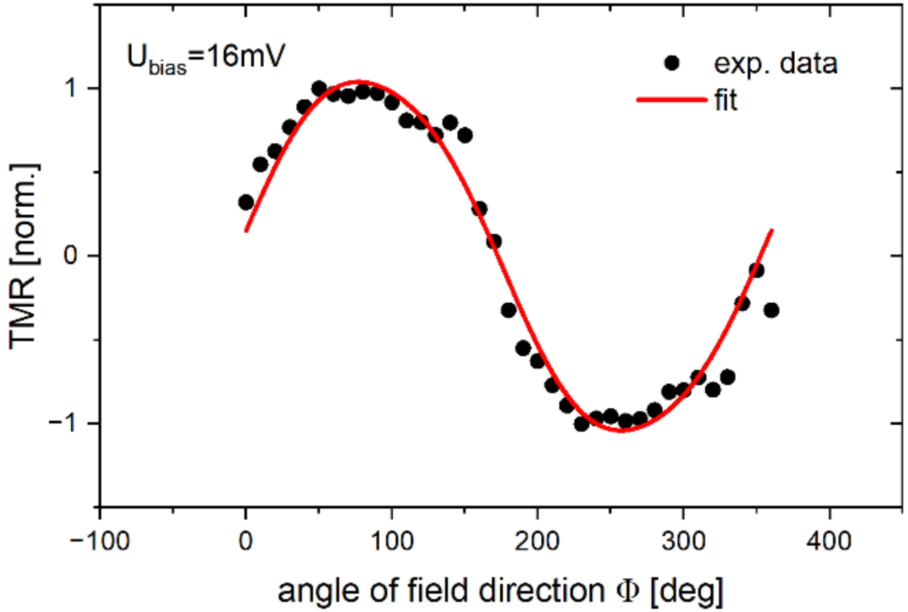
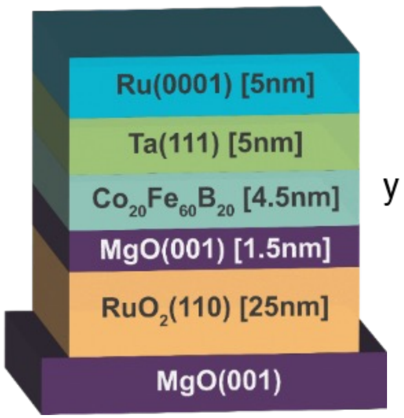
Tunneling MR in RuO_2/MgO/CoFeB
$\vec{H}$ in plane









simple two-domain fitting model:

$$y = \text{Amp.} \cdot \left\{ \left(\frac{1}{R_0 + \sin(x + phase) * Twin\_A} + \frac{1}{R_0 + \cos(x + phase) * (1 - Twin\_A)} \right)^{-1} - \left(\frac{1}{R_0 + \sin(x + 180° + phase) * Twin\_A} + \frac{1}{R_0 + \cos(x + 180° + phase) * (1 - Twin\_A)} \right)^{-1} \right\}^{-1}$$

Twinning analysis:

from XRD:
Twin A: 42.8%
Twin B: 57.2%

from TMR fit:
Twin A: 43.0%
Twin B: 57.0%

→ reasonable agreement

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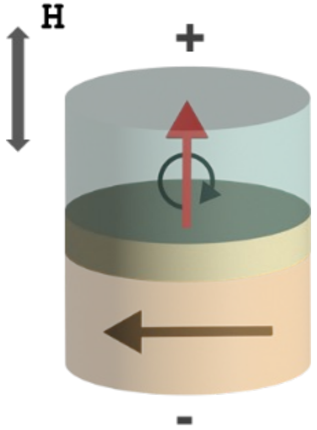
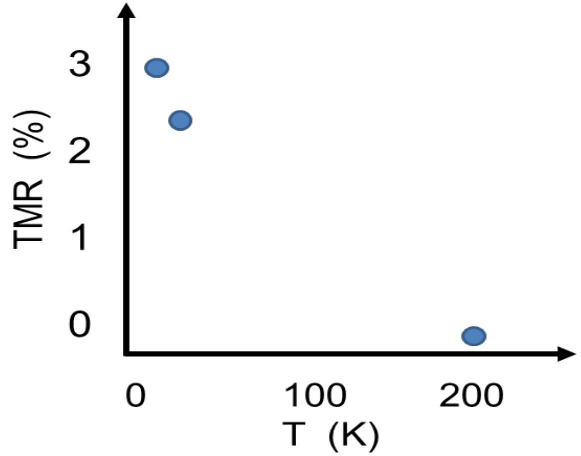
Tunneling MR in $RuO_2/MgO/CoFeB$

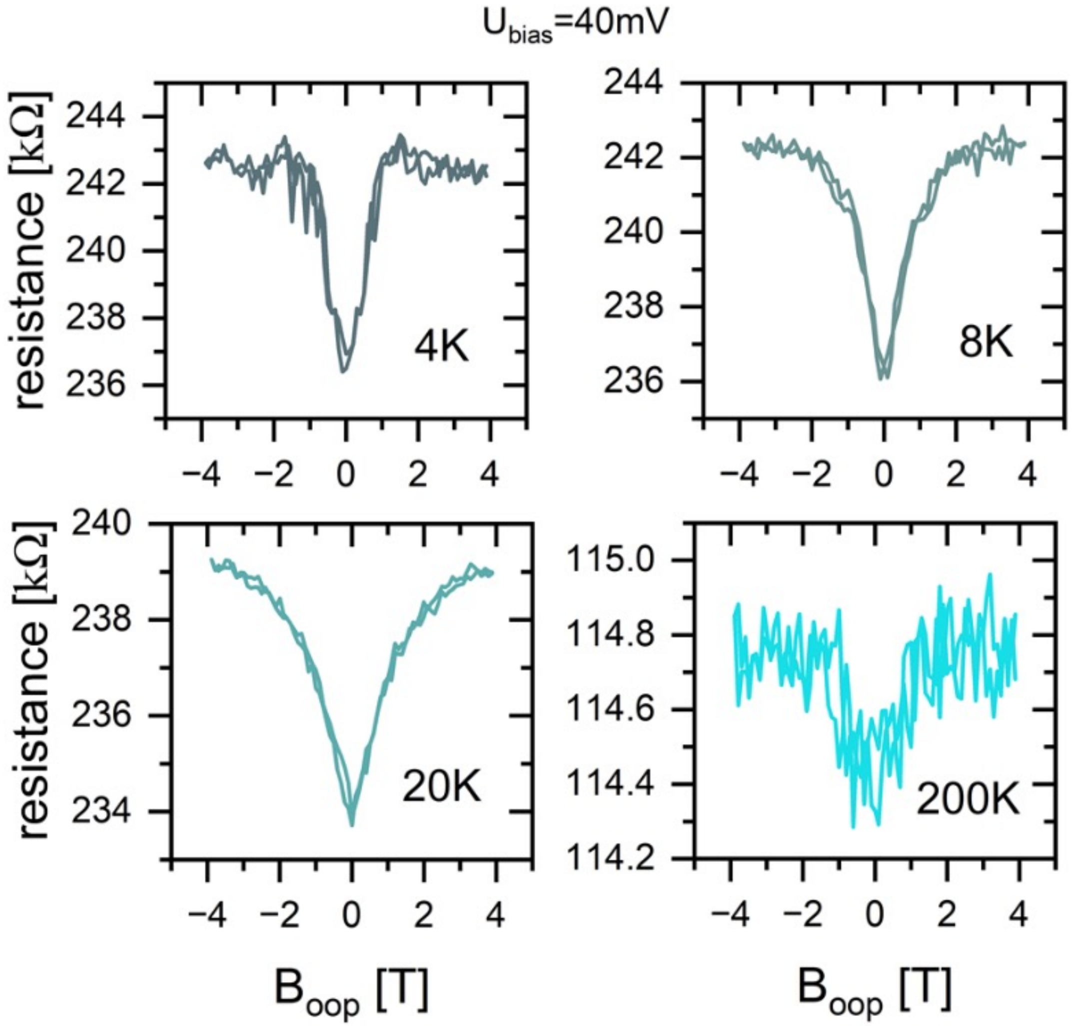
Temperature dependence of the oop-TMR



Critical temp. above RT

TMR still visible at 200K





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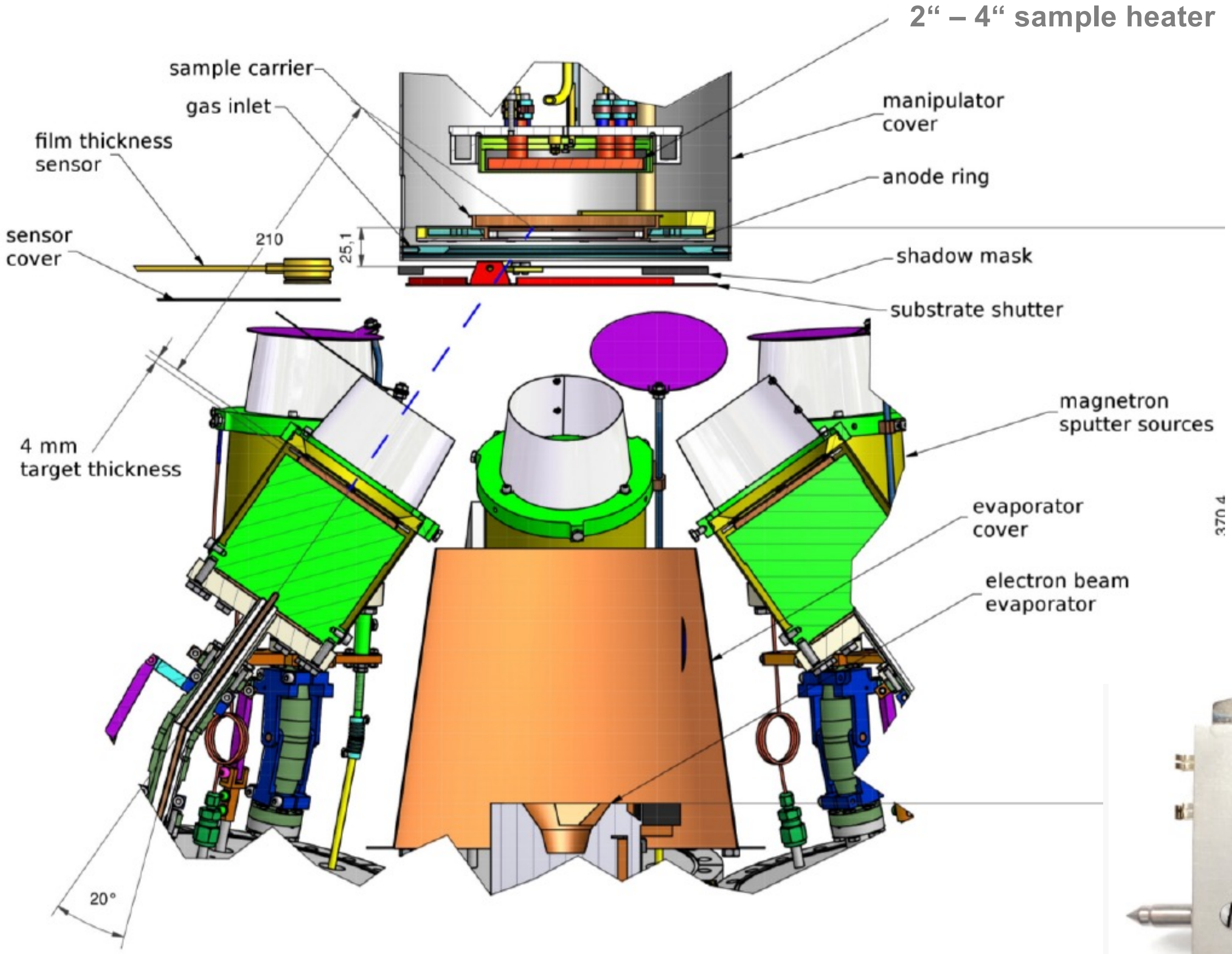
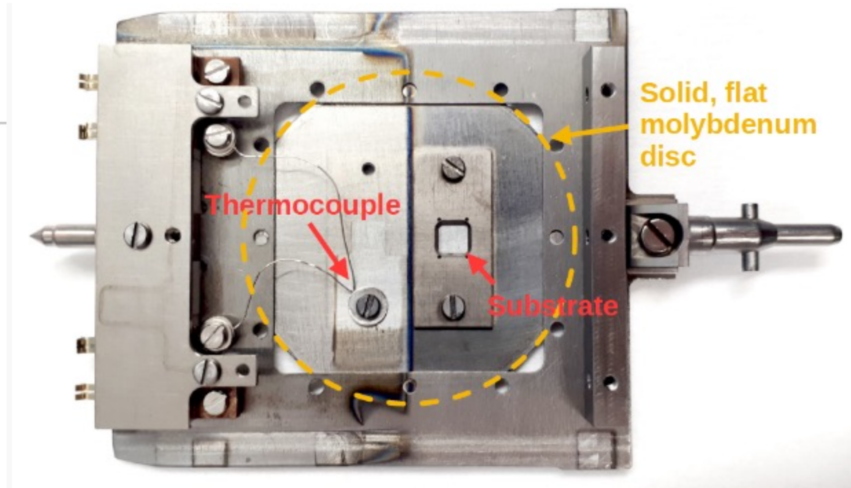
Maximilian
Koll

Altermagnets Mn_XSi_Y



Deposition via
co-sputtering
of Mn and Si

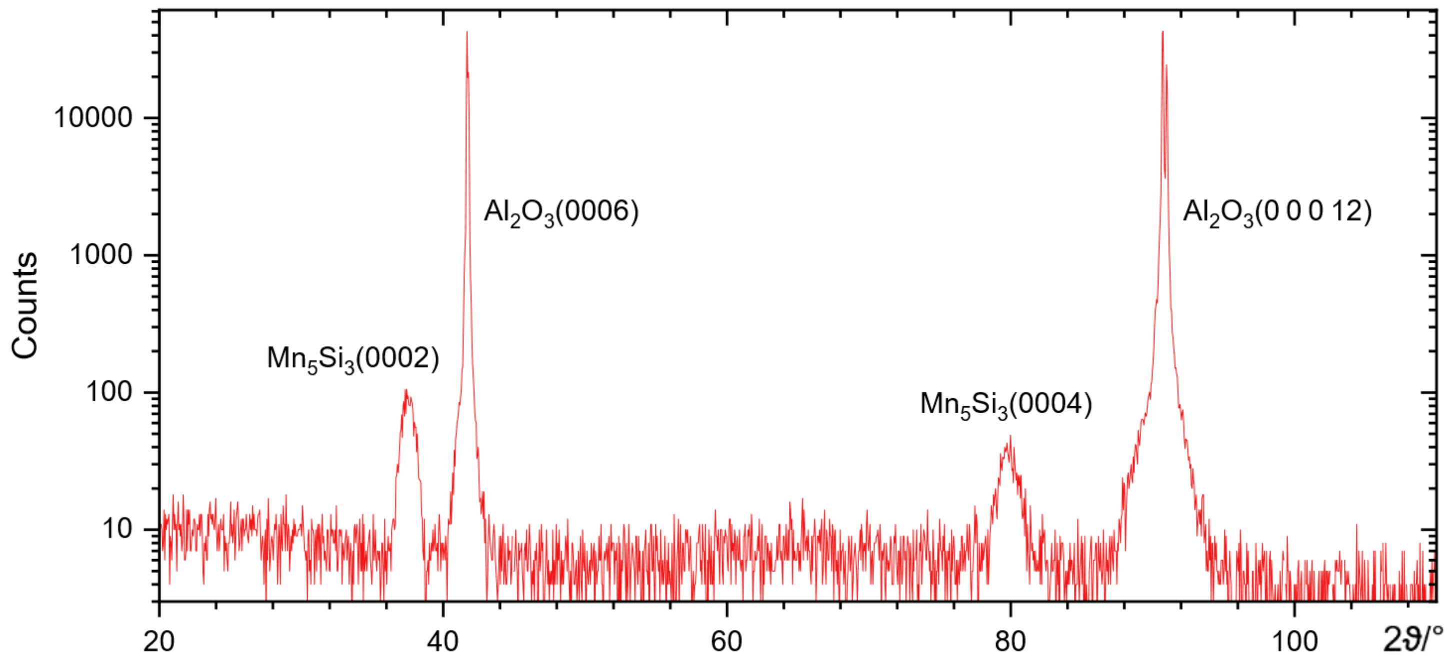
@ different
substrate temperatures



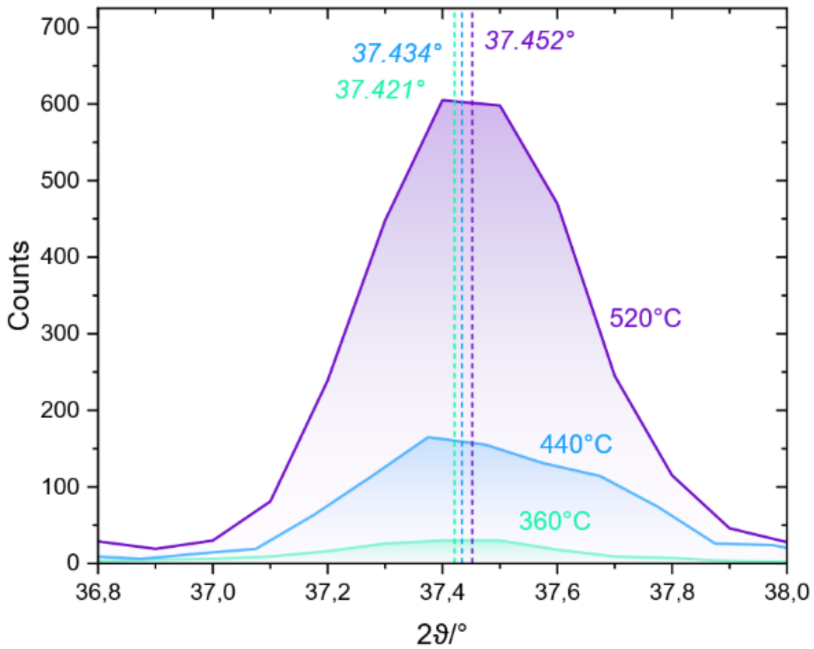
Maximilian Koll

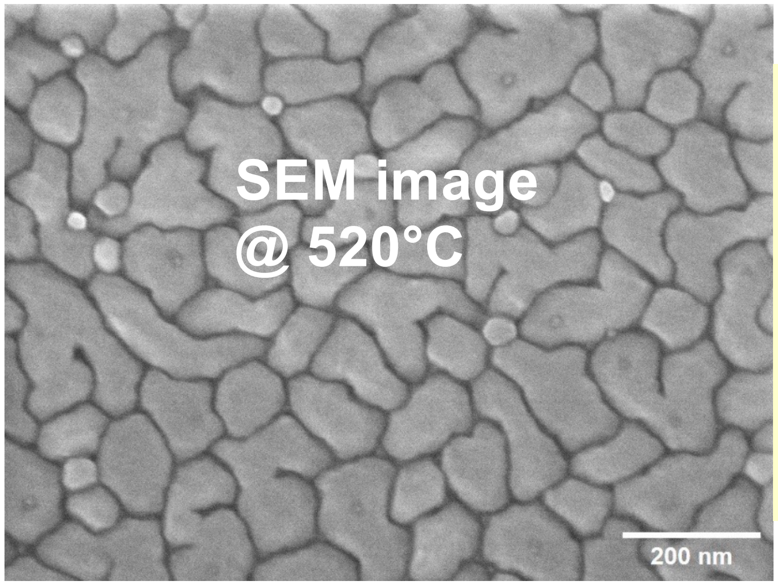
.. works on progress

Altermagnets Mn_XSi_Y



Highly textured growth of Mn_5Si_3 in (0001) direction



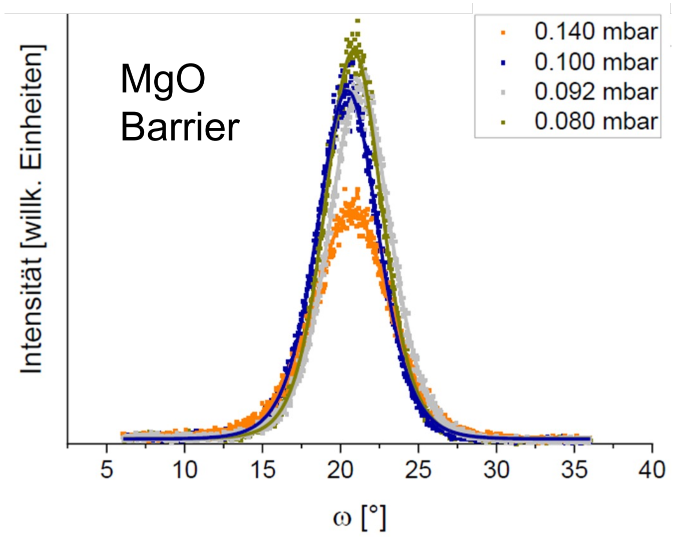


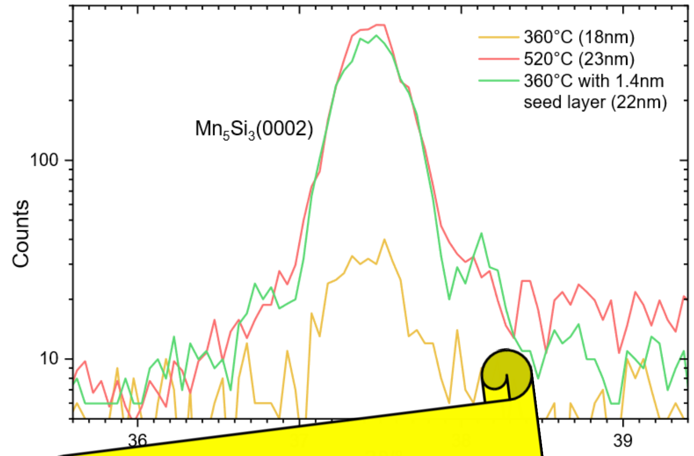
Mn_5Si_3 crystals with about 0.5° FWHM

Island growth with infinite resistance for T_{Dep} > 360°C

Outlook

- **RuO_2:**
  - **Confirm, if Neél vector switching is present**
  - **Improve tunneling barrier**
- **Modify growth of Mn_XSi_Y**
- **TMR and GMR in Altermagnet-Devices**
- **Spincaloric effects (T. Kuschel)**





Many thanks to

K. Rott, J.-M. Schmalhorst, I. Ennen, A. Thomas, T. Kuschel, L. Kempe, N. Schmolka, F. Knossalla, F. Peters, M. Koll, M. Gärner