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Role of thermal activation in the spin-orbit torque switching of antiferromagnets

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Outline

1. Thermal activation in the Néel-order switching of Mn_2Au

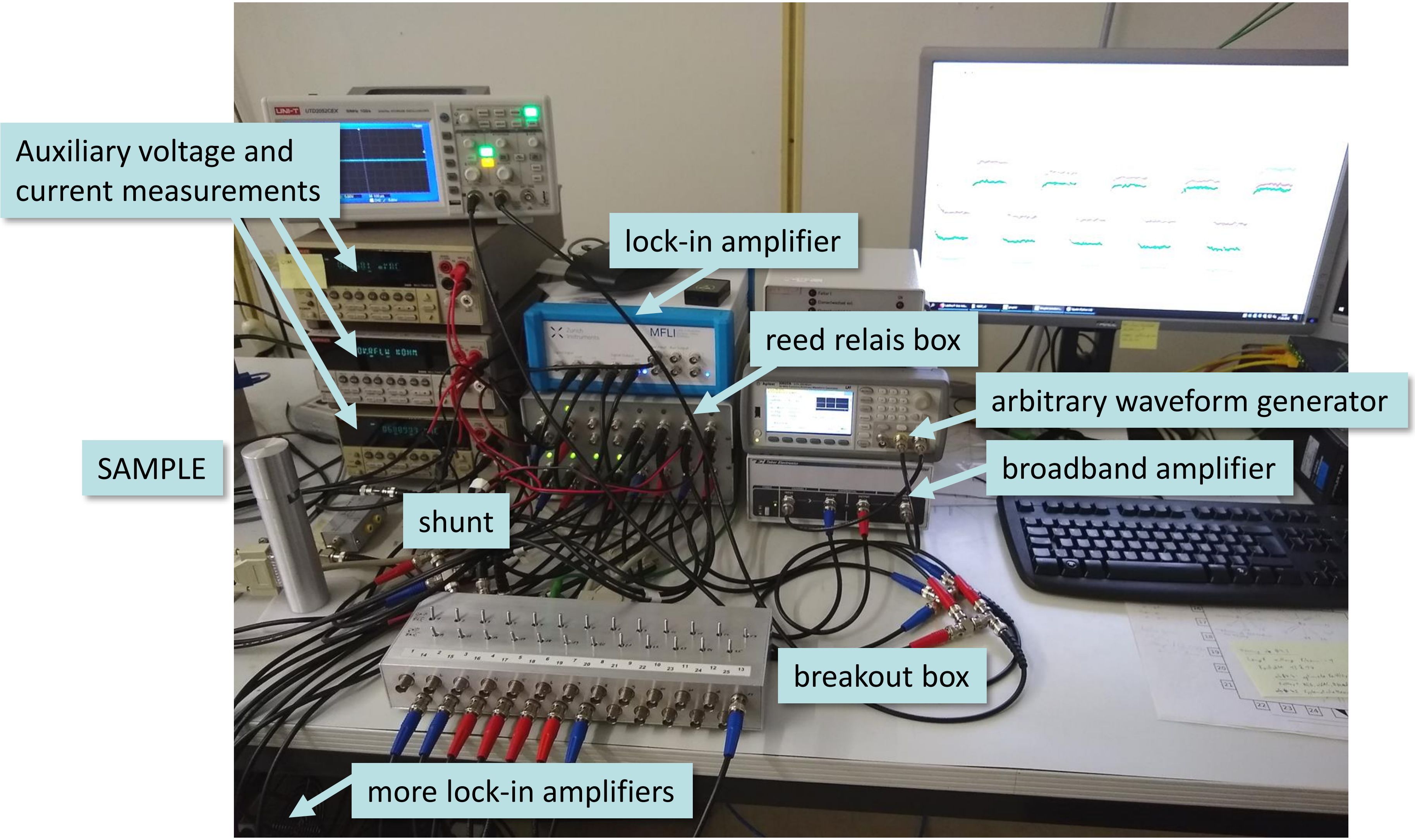
2. Néel-order switching in magnetron-sputtered CuMnAs films

3. Electrical switching of the Néel order in MnN with the spin Hall effect of Pt

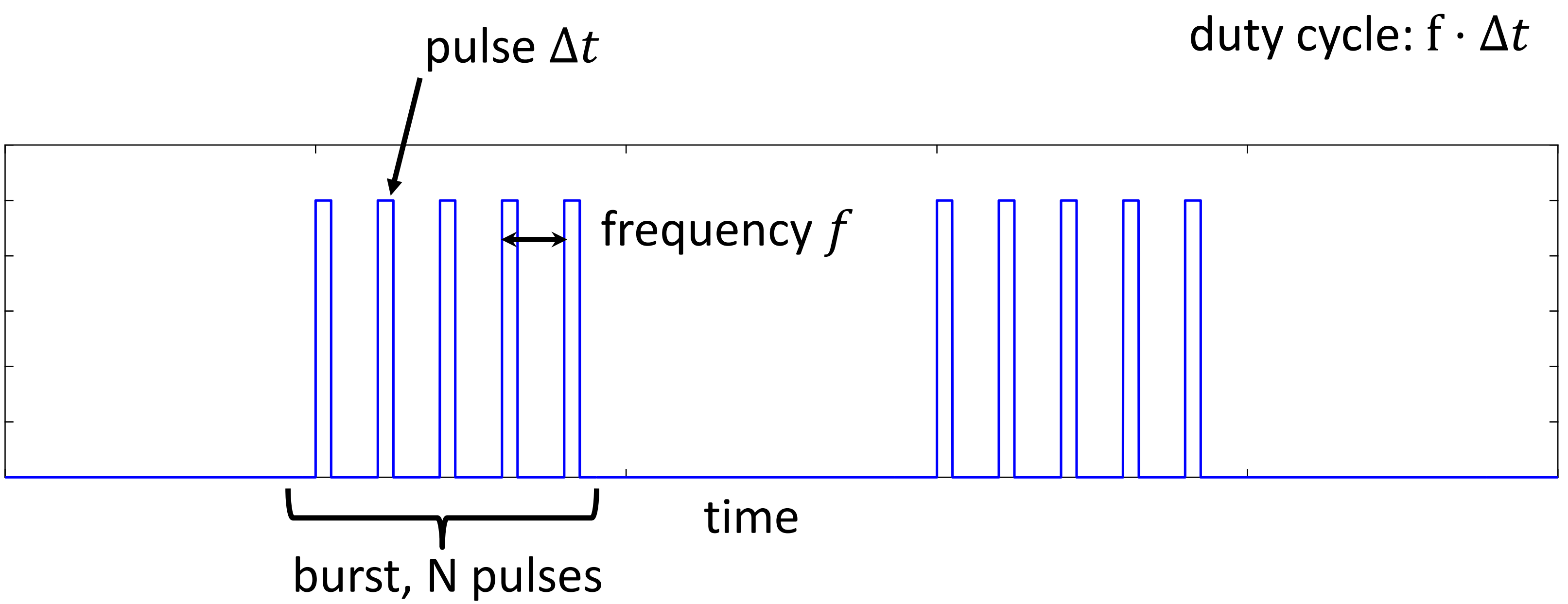
4. Ohmic contributions to the electrical read-out

Thermal activation in the Néel-order switching of Mn_2Au

Electrical observation of the Néel-order switching

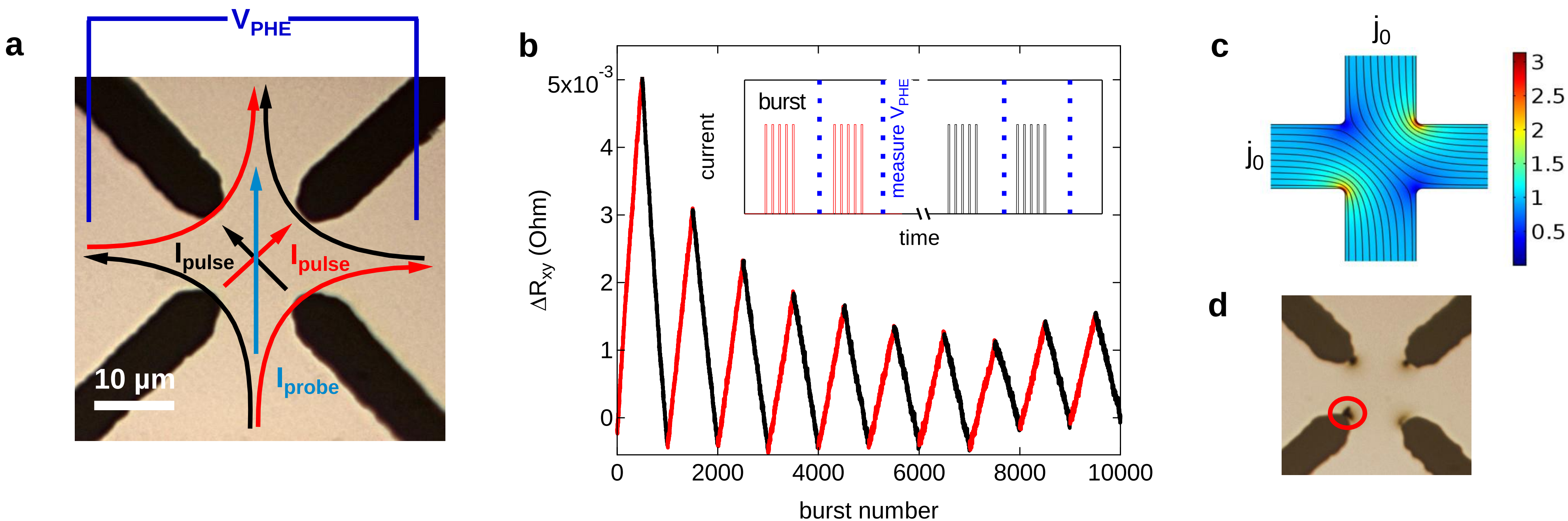


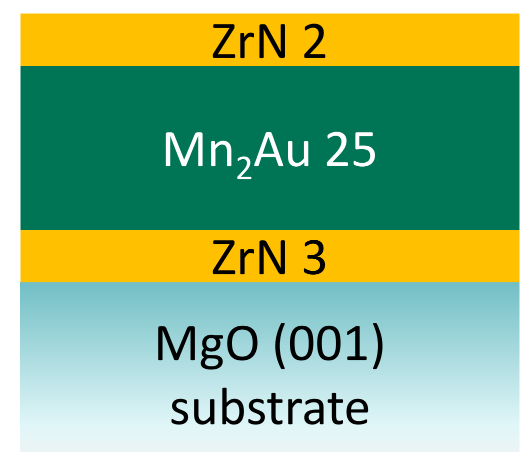
Pulses and bursts



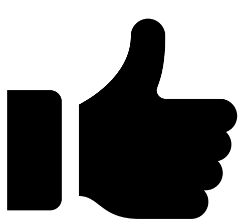
- Long single pulse heats the film
- ➢ Chop the single pulse into N shorter pulses
- ➢ Keep the total charge per burst constant, i.e. $Nj\Delta t = const.$

Electrical switching of Mn_2Au





Electrical switching of Mn_2Au is observed!



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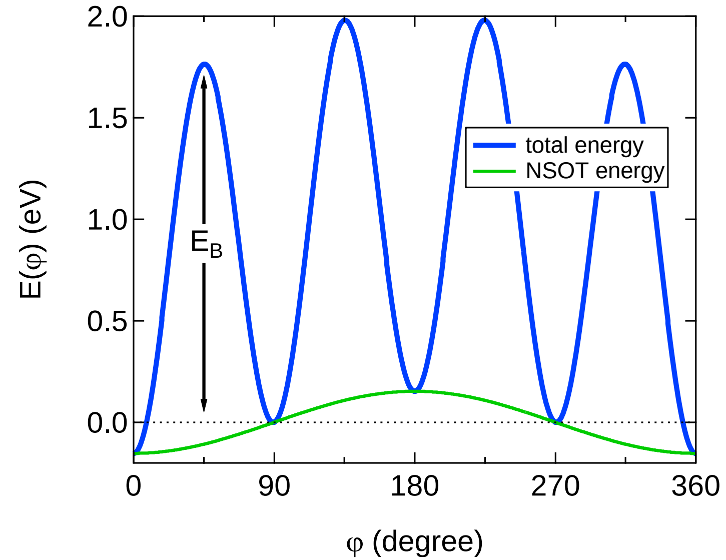
Thermal activation model - Part I

Idea: Uncoupled grains, coherent switching.



Energy:

$$E/V_g = K_{4\parallel} \sin^2 2\varphi - \boldsymbol{L} \cdot \boldsymbol{B}_{\mathrm{eff}}/V_{\mathrm{cell}}$$

Energy barrier:

$$E_{\mathrm{B}} = \min_{cw,ccw} \left(\max_{[\varphi_i,\varphi_f]} [K_{4\parallel} \sin^2 2\varphi - (\boldsymbol{L} \cdot \boldsymbol{B}_{\mathrm{eff}})/V_{\mathrm{cell}}] - E(\varphi_i) \right)$$

Effective field:

$$\boldsymbol{B}_{\mathrm{eff}} = (\boldsymbol{j} \times \boldsymbol{z}) \cdot \chi$$

$K_{4\parallel}$: anisotropy energy density
V_{g}: grain volume
V_{cell}: unit cell volume
χ: spin-orbit torque efficiency

Thermal activation model - Part II

Switching rate (Néel-Arrhenius):

$$\frac{1}{\tau} = f_0 \mathrm{e}^{-\frac{E_\mathrm{B}}{k_\mathrm{B}T}}$$

Switching probability:

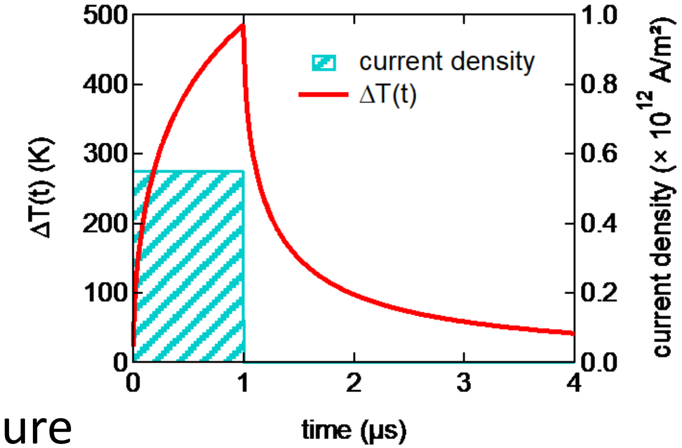
$$P_{SW}(\Delta t) = 1 - e^{-\Delta t/\tau}$$

Film temperature:

$$T(t,\Delta t) = T_0 + \frac{2whj^2}{\pi\kappa_S\sigma}\left(\operatorname{arcsinh}\left(\frac{2\sqrt{\kappa_S t/\rho_S C_S}}{\alpha w}\right) + \Theta(t-\Delta t)\operatorname{arcsinh}\left(\frac{2\sqrt{\kappa_S (t-\Delta t)/\rho_S C_S}}{\alpha w}\right)\right)$$

f_0: attempt rate

Δt: pulse width



T_0: base temperature
d: film thickness
w: current channel width
σ: electrical conductivity
ρ_S: density of the substrate
C_S, κ_S: thermal parameters of the substrate

C.-Y. You et al., Appl. Phys. Lett. **89**, 222513 (2006).

Model parameters and PHE calculation

K = fitting parameter

$V_g = \frac{\pi D^2}{4} h,\ D = 22\text{nm},\ d = 25\text{nm}$

$V_{\text{cell}} = 4.75 \times 10^{-29}\text{m}^3$

$|\boldsymbol{L}| = 2 \times 4\mu_B$

$\chi = 0.2\text{mT}/(10^{11}\text{A/m}^2)$

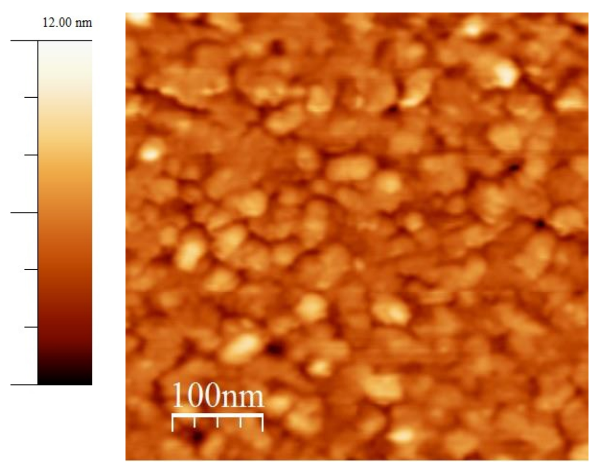
$f_0 = 10^{12}\text{s}^{-1}$

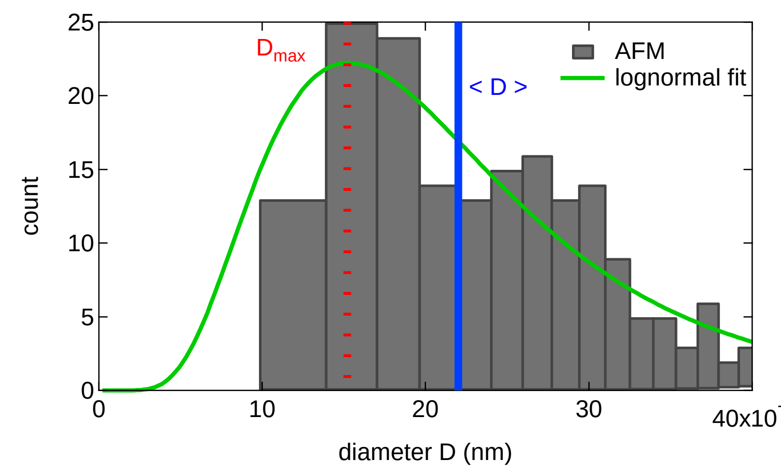
$w \approx 12\mu\text{m}$

$\sigma = (73\mu\Omega\text{cm})^{-1}$

$\Delta R_{xy} = A \langle \sin 2\varphi \rangle$

$A \approx 1\Omega$





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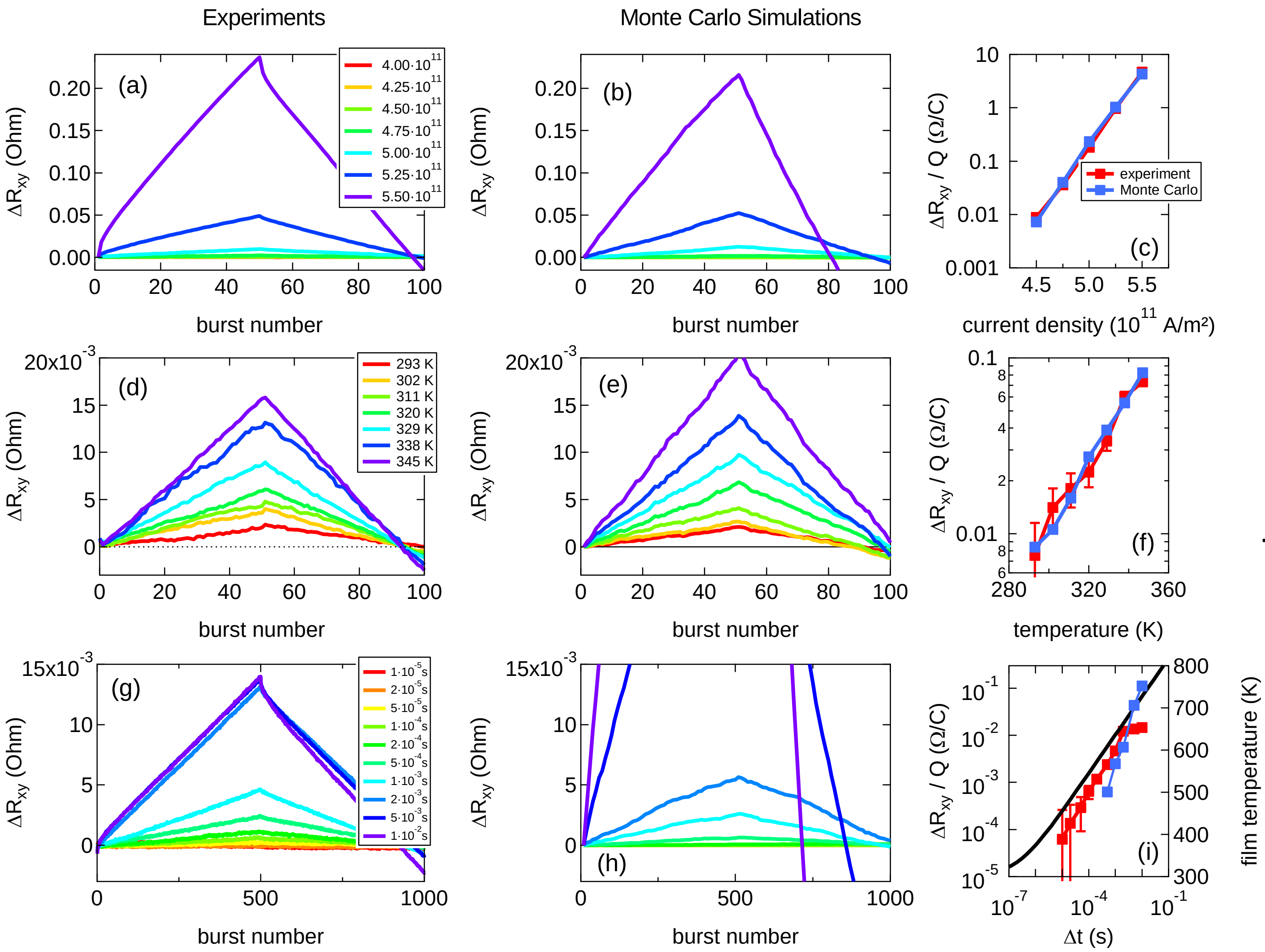
Experiment vs. theory



Anisotropy energy per grain:

$$K_{4\parallel}V_g \approx 1.5\text{eV}$$

Anisotropy energy density:

$$K_{4\parallel}V_g \approx 7.5\ \mu\text{eV/f.u.}$$

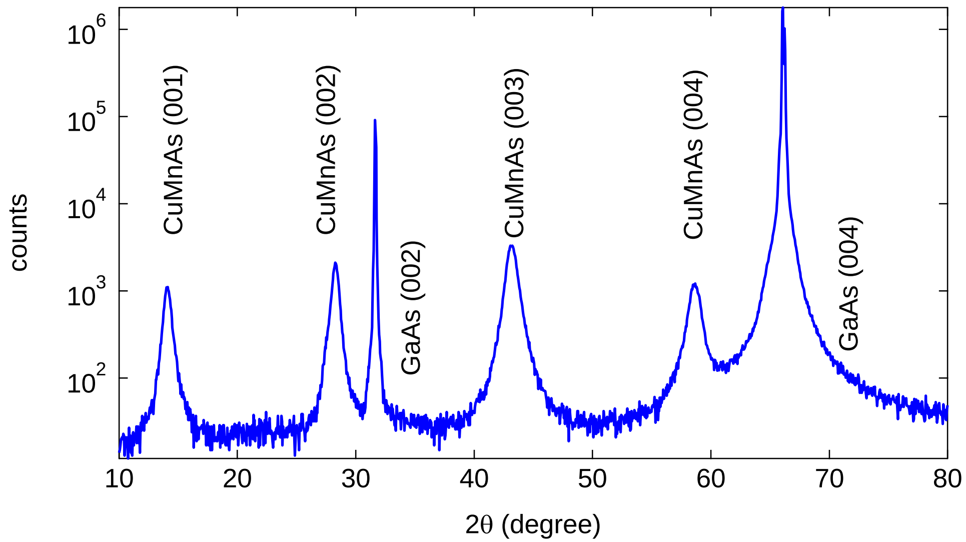
Thermal stability factor at RT:

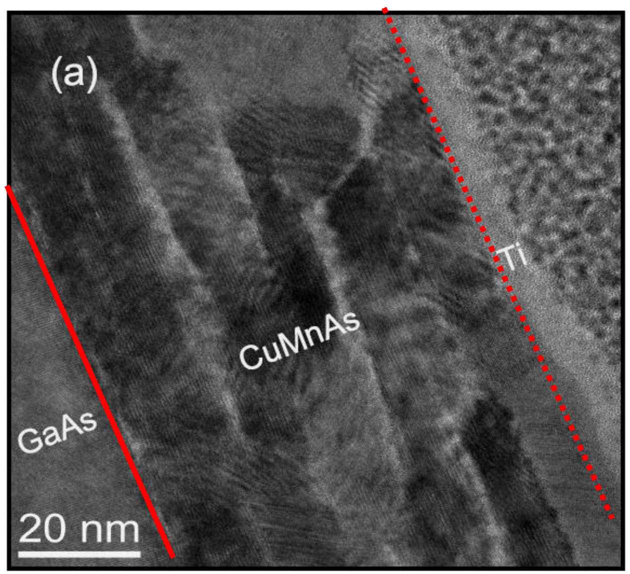
$$\Delta = \frac{KV_g}{k_B T} \approx 60$$

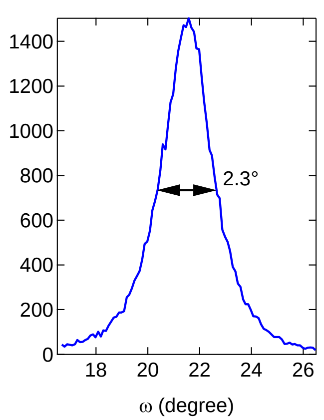
M. Meinert et al., Phys. Rev. Applied **9**, 064040 (2018)

Néel-order switching in magnetron-sputtered CuMnAs films

Magnetron-sputtered CuMnAs



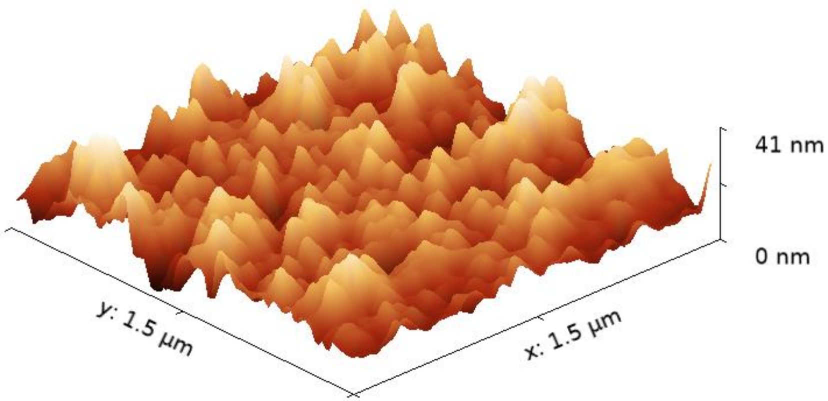




- Growth of CuMnAs from alloy target
- Substrate temperature: $410°C$

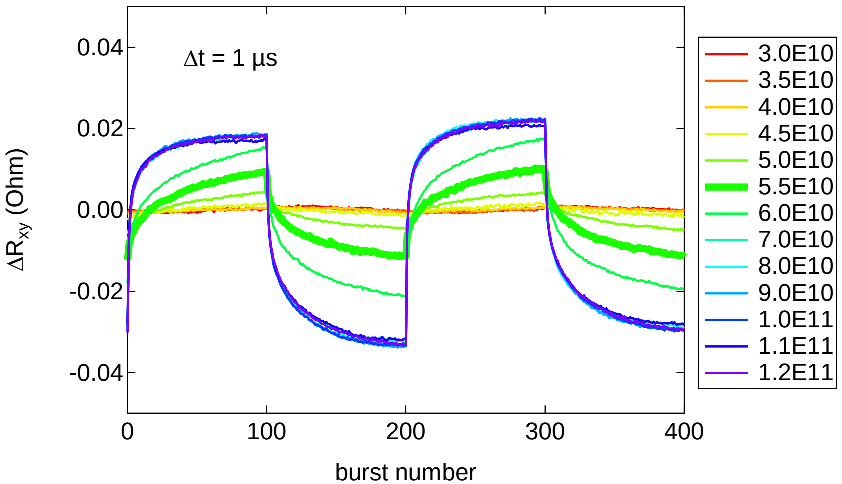
GaAs (001) / CuMnAs 100 nm / Ti 3nm

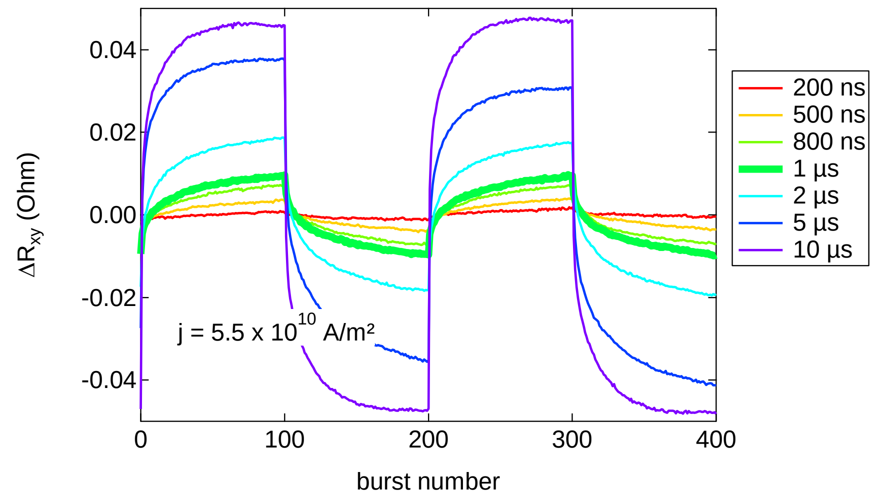
- Oriented growth of tetragonal CuMnAs with preferred (001) direction
- Perpendicular grain size $\approx 10nm$
- Large surface roughness

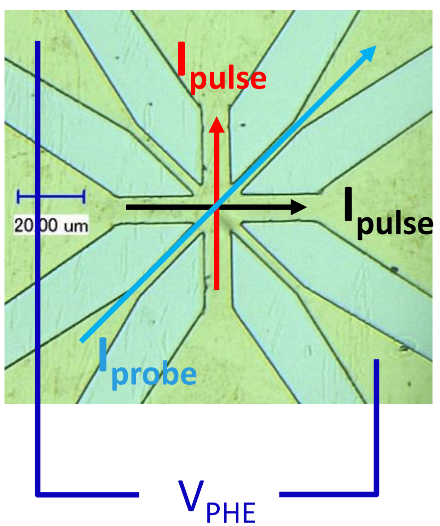


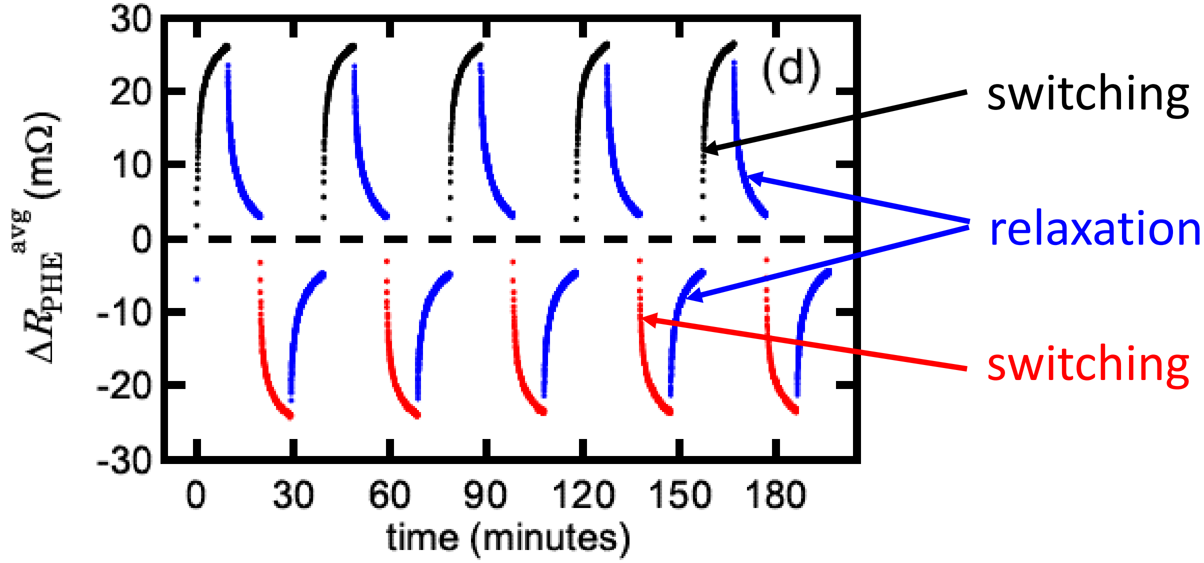
T. Matalla-Wagner, MM, et al., arXiv:1903.12387

Electrical switching of CuMnAs



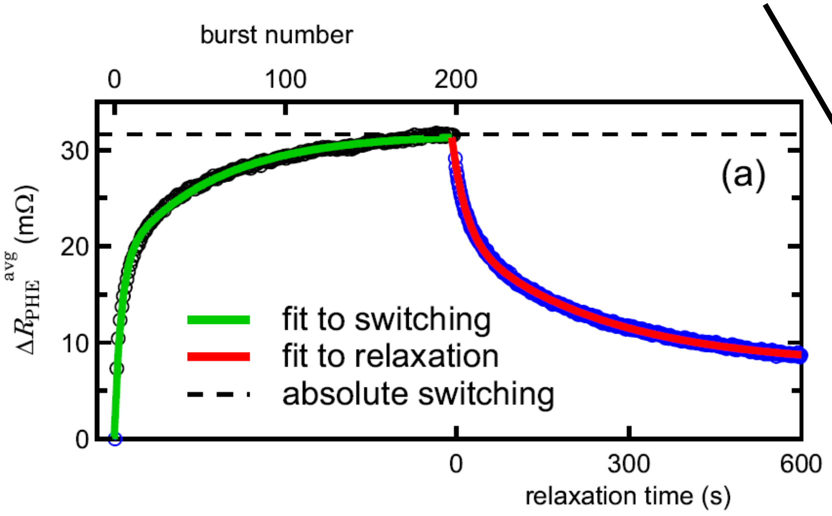






T. Matalla-Wagner, MM, et al., arXiv:1903.12387

Parameter extraction



Empirical fit of pulsing- and relaxation-phases

$$R_{\mathrm{p}}(b) = R_{0,\mathrm{p}} + c_1 \exp\left(-\frac{b}{\mu_1}\right) + c_2 \exp\left(-\frac{b}{\mu_2}\right)$$

$$R_{\mathrm{r}}(t) = R_{0,\mathrm{r}} + d_1 \exp\left(-\frac{t}{\tau_1}\right) + d_2 \exp\left(-\frac{t}{\tau_2}\right)$$

$$R_{\mathrm{e}} = \left| \left.\frac{\mathrm{d}R_{\mathrm{p}}(b)}{\mathrm{d}b}\right|_{b=0} \right|$$

Solution of our model equations in linear response:

$$\left|\Delta R_{\mathrm{PHE}}^{\mathrm{burst}}\right| \approx \frac{QAf_0}{jwh} \exp\left(\frac{L\chi V_{\mathrm{g}} j}{\sqrt{2} k_{\mathrm{B}} T V_{\mathrm{c}}} - \frac{E_{\mathrm{B}}}{k_{\mathrm{B}} T}\right)$$

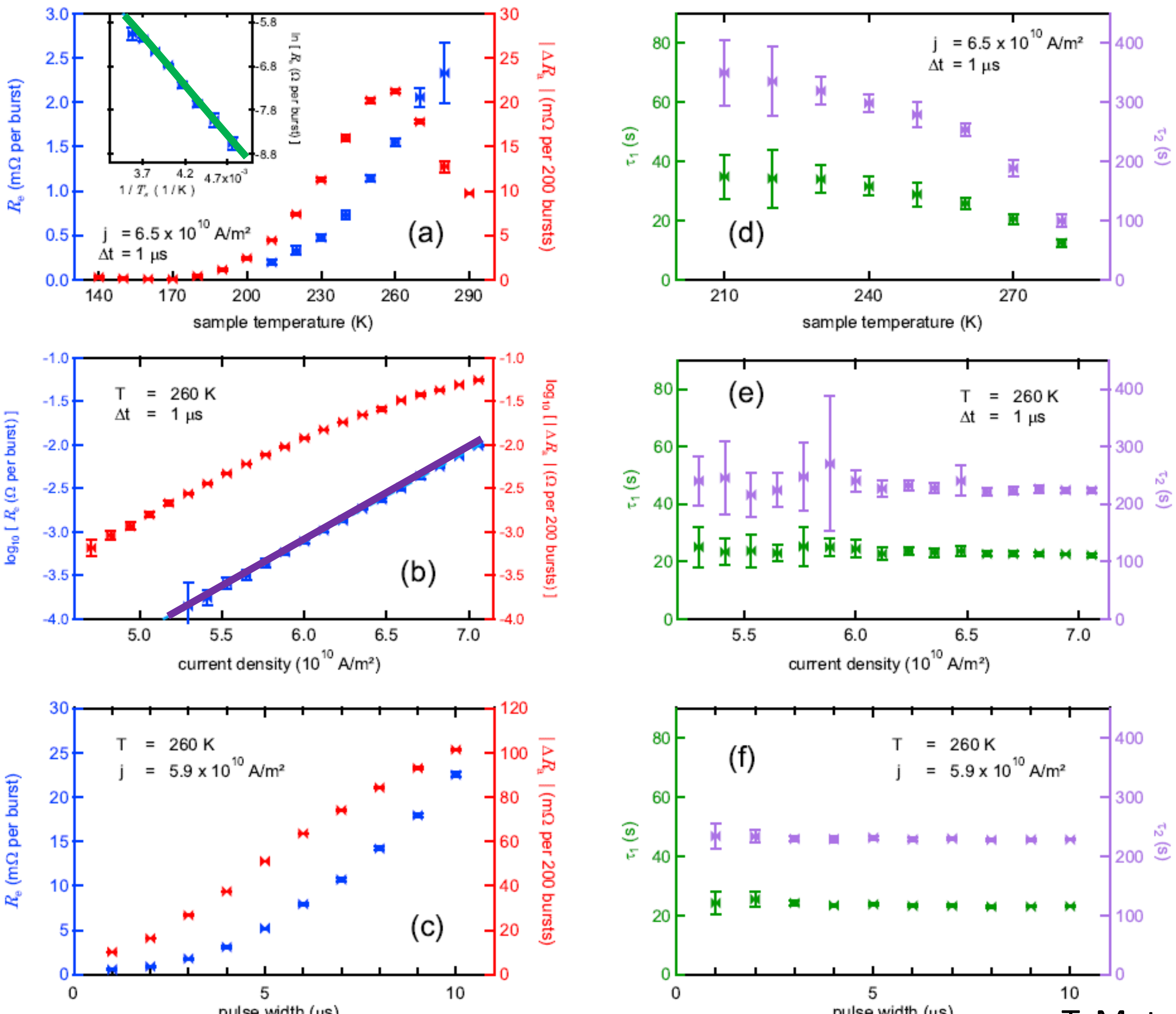
Exact solution for decay (relaxation):

$$R_{\mathrm{PHE}}(t) = R_{\mathrm{PHE}}(t=0) \exp\left(-\frac{t}{\tau}\right)$$

$$E_B^i = \ln\left(f_0 \tau_i\right) k_B T_{\mathrm{s}}$$

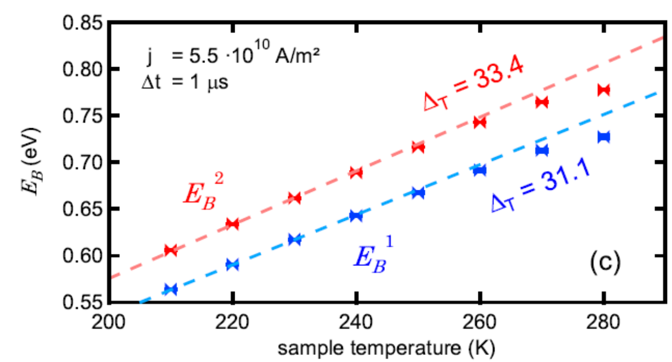
T. Matalla-Wagner, MM, et al., arXiv:1903.12387

Dependences on $T, j, \Delta t$



$$\ln R_e = k_1 + \frac{k_2}{T}$$

$$\ln R_e = m_1 j + m_2 + \ln j$$

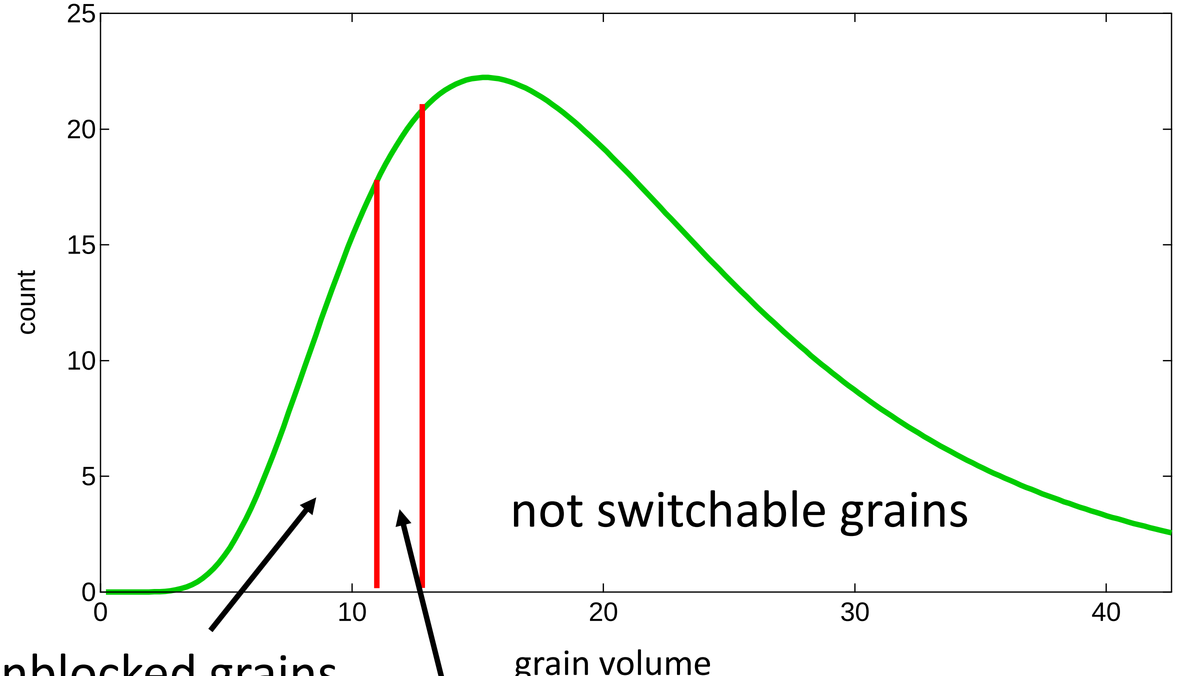


$$E_B^i = \ln\left(f_0 \tau_i\right) k_B T_s$$

We switch grains with lower barrier at lower temperature, because χ is constant!

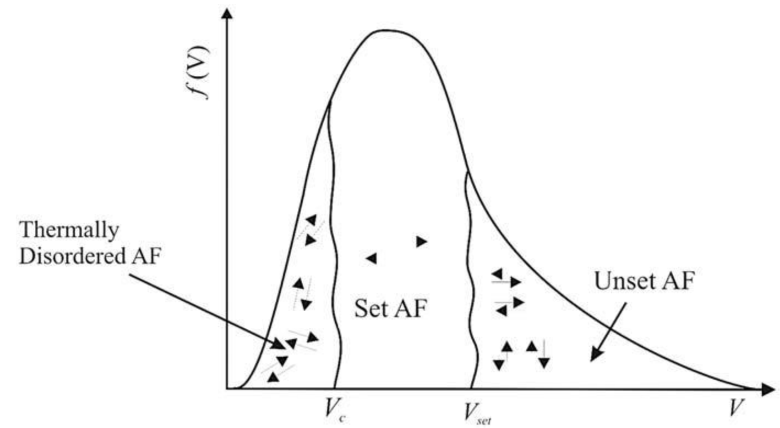
T. Matalla-Wagner, MM, et al., arXiv:1903.12387

Size matters: grain size distribution and (un-)blocking



unblocked grains

switchable grains, just blocked at T_0
"active part" of the distribution, changes with T_0

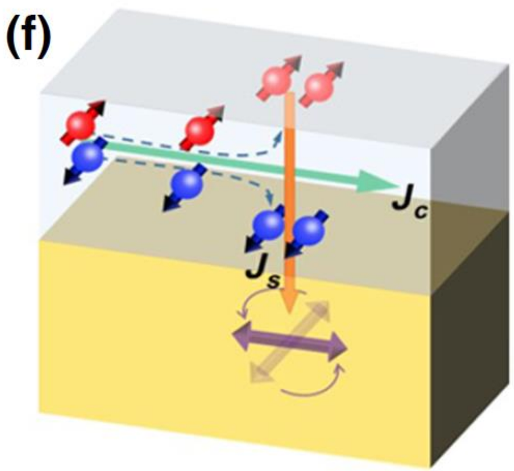


Inspired by **exchange bias** physics!
K. O'Grady et al.
J. Magn. Magn. Mater. **322**, 883 (2010)

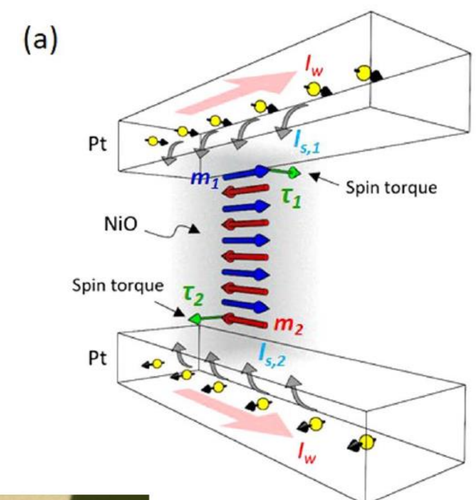
Joule heating makes blocked grains switchable!
The switching must be thermally assisted! Otherwise, long-term retention of written state is impossible.

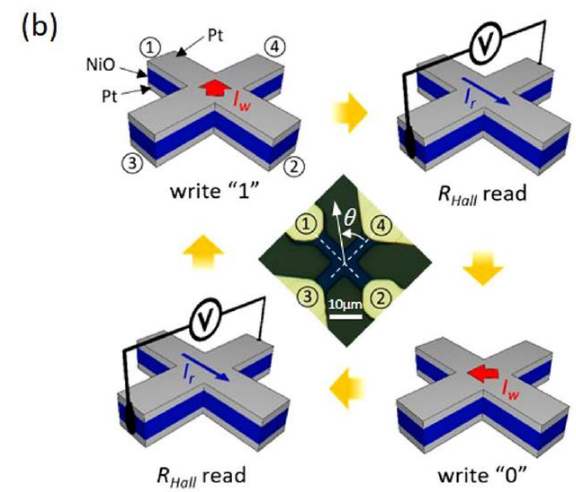
Electrical switching of the Néel order in MnN with the spin Hall effect of Pt

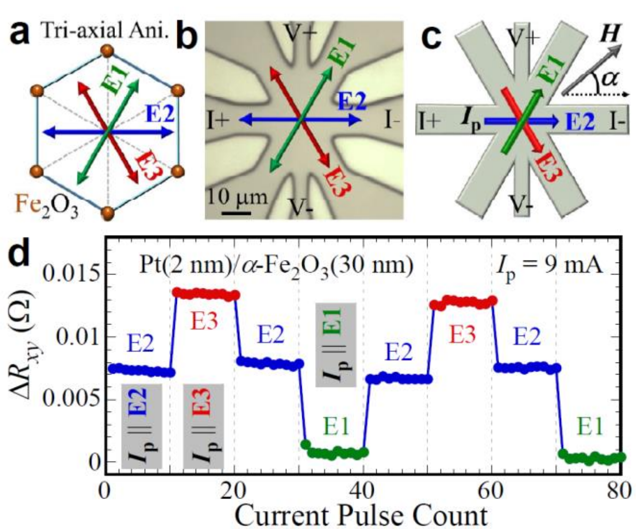
Switching antiferromagnets with the spin Hall effect

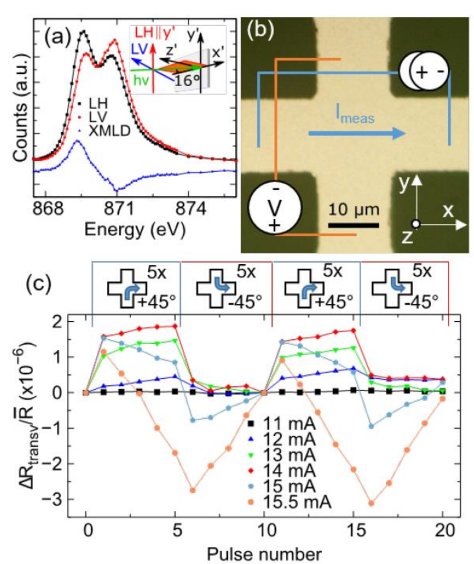


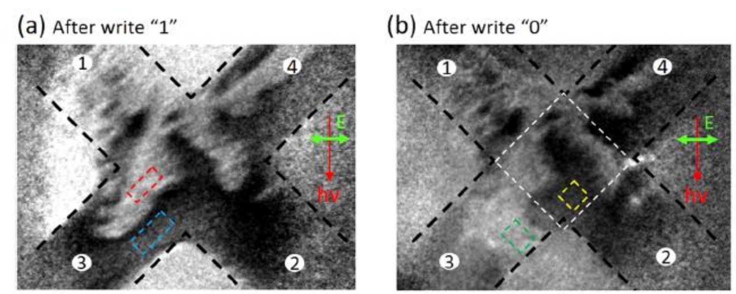
Spin current due to spin Hall effect favors $\boldsymbol{n} \parallel \boldsymbol{j_c}$







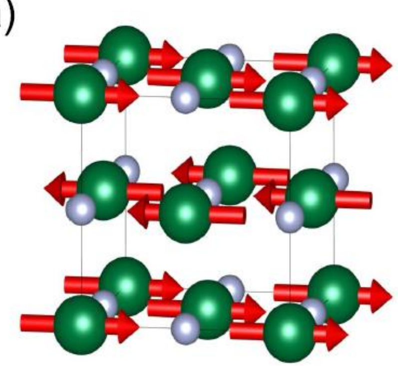




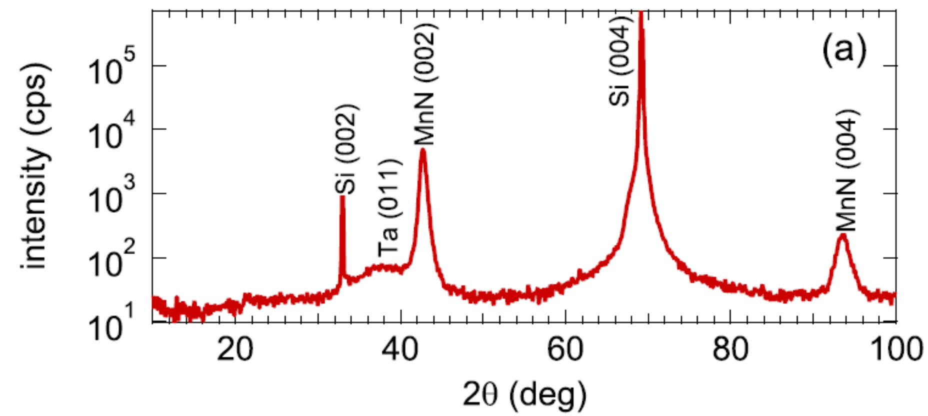
X. F. Zhou et al., Phys. Rev. Appl. **11**, 054030 (2019)
Baldrati et al., arXiv: 1810.11326v2
T. Moriyama et al., Sci. Rep. **8**, 14167 (2018)
Y. Cheng et al, arXiv:1906.04694

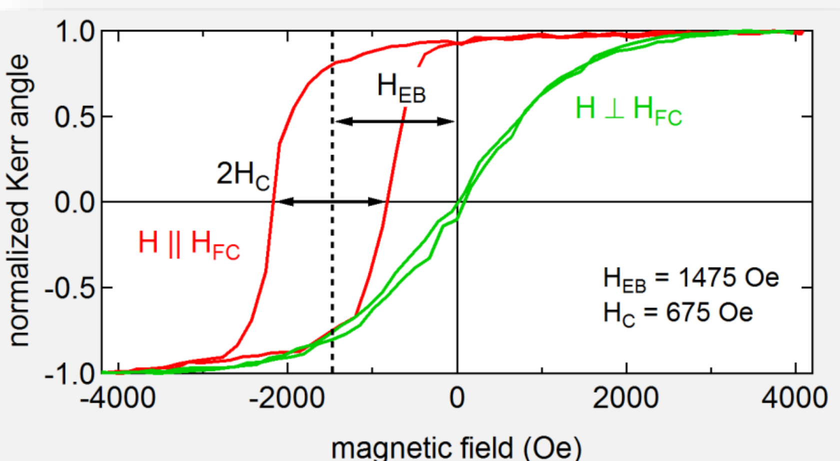
The antiferromagnet MnN

a)

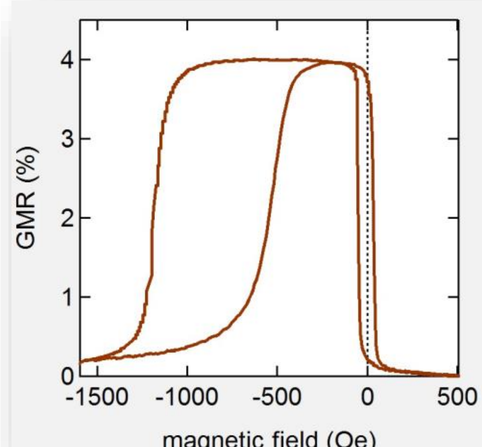


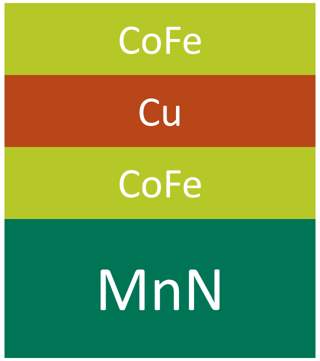
$$T_N = 650K$$





Ta 10 / **MnN 32 / CoFe 1.6** / Ta 2





M. Meinert et al., Phys. Rev. B **92**, 144408 (2015)

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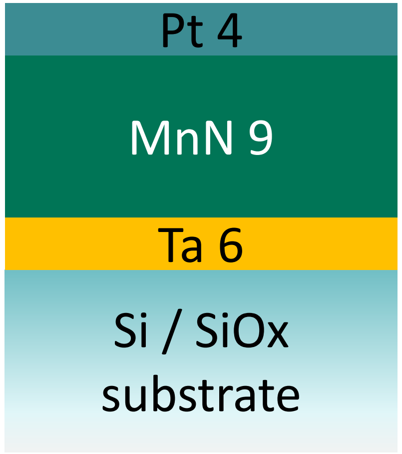
Electrical switching of MnN

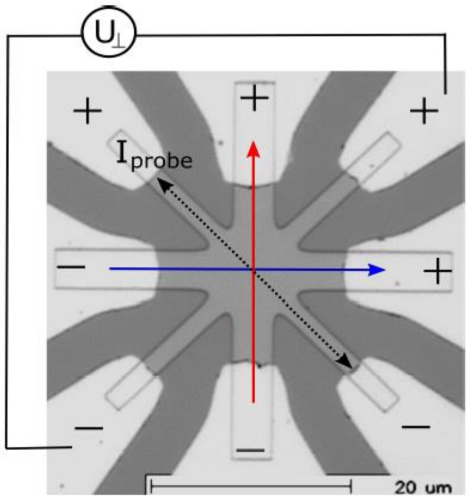


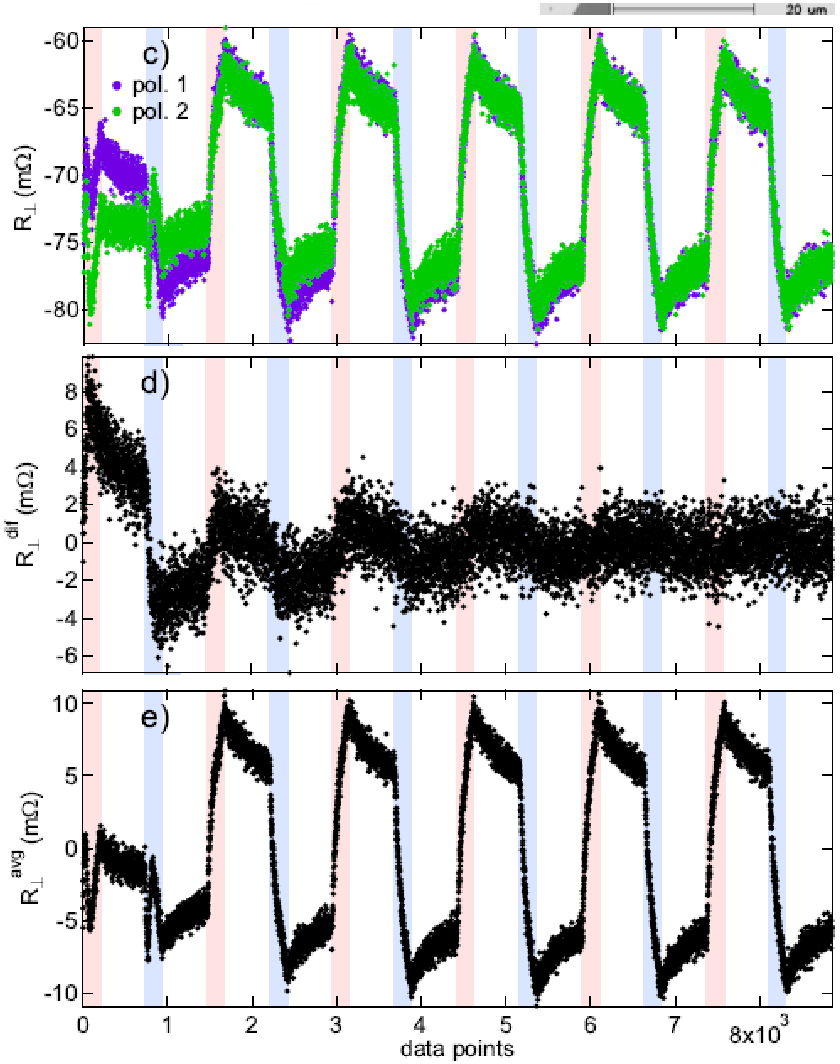
← $\rho \approx 25\ \mu\Omega\text{cm}$

← $\rho \approx 200\ \mu\Omega\text{cm}$

← $\rho \approx 180\ \mu\Omega\text{cm}$

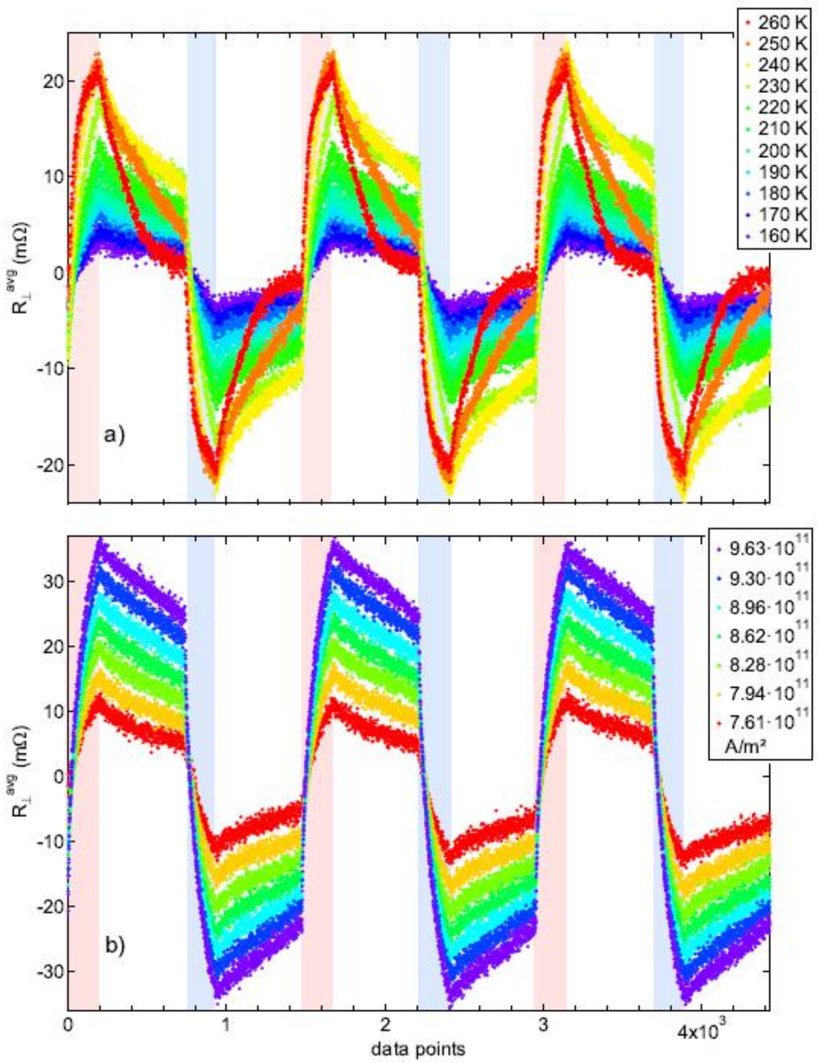
b)

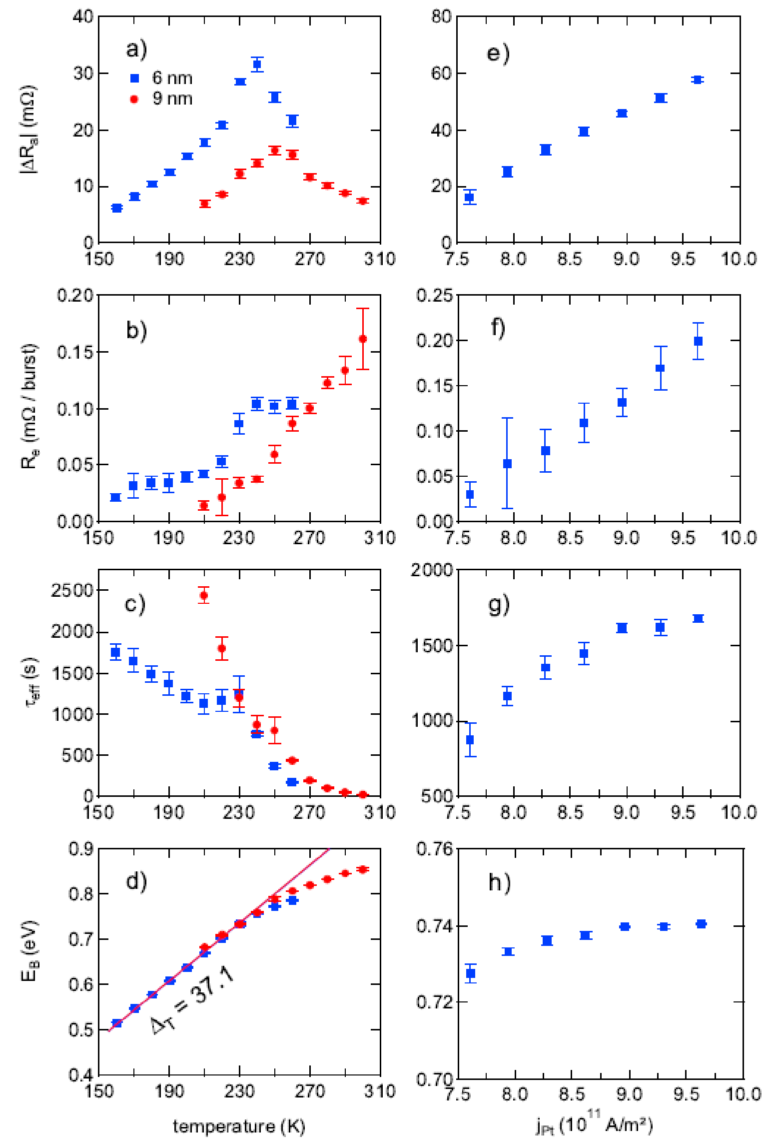




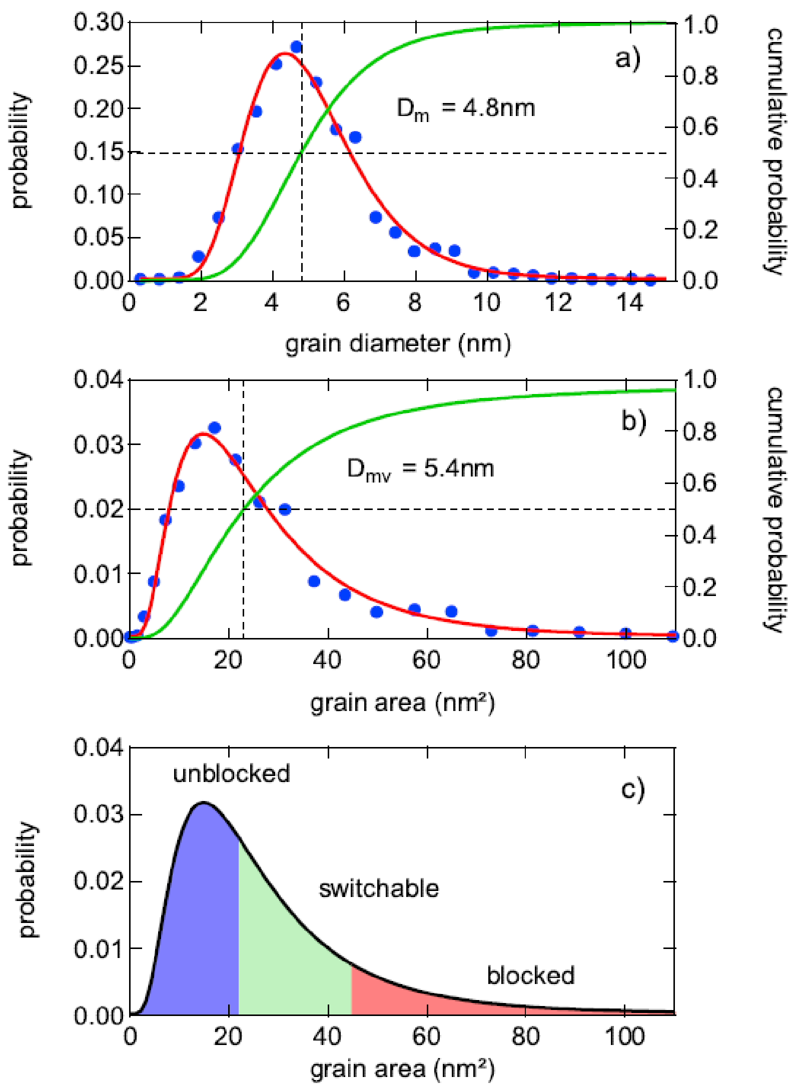
M. Dunz, T. Matalla-Wagner, M. Meinert, arXiv:1907.02386

Electrical switching of MnN: Parameters

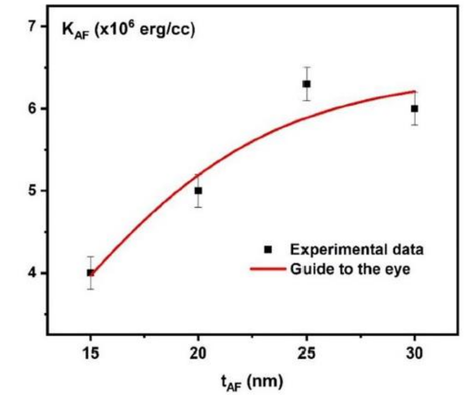




Grain size analysis

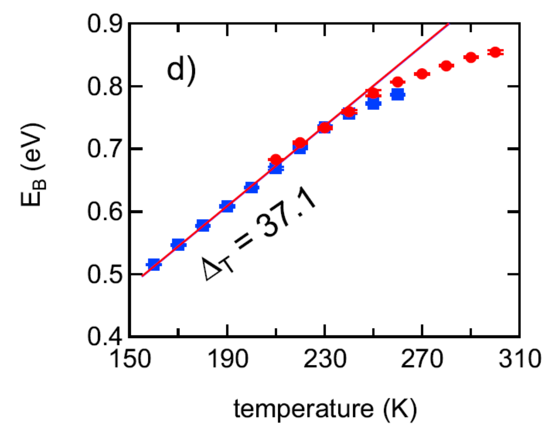


Anisotropy analysis via "York protocol":



$\langle E_B \rangle \approx 0.5\text{eV}$
@ 9nm

Energy barrier from switching and relaxation:



J. Sinclair et al., J. Magn. Magn. Mater. **476**, 278 (2019)
M. Dunz, T. Matalla-Wagner, M. Meinert, arXiv:1907.02386

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Ohmic contributions to the electrical read-out

UNPUBLISHED

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Antiferromagnetic Spintronics

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Jan Albrecht

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Satya Prakash Bommanaboyena
Lukas Neumann
Christan Mehlhaff
Sebastian Dapper
Kevin Diekmann
Dominik Graulich
Philipp Zilske

Prof. Dr. Günter Reiss

Nobumichi Tamura, ALS Berkely
Hubert Ebert, LMU Munich

DFG Deutsche Forschungsgemeinschaft

Ministerium für Innovation, Wissenschaft und Forschung des Landes Nordrhein-Westfalen