Quench-switching of antiferromagnetic CuMnAs using ultrashort pulses

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European Research Council
Established by the European Commission
Horizon 2020 - FET Open
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Outline

Quench switching of magnetic state in CuMnAs

- Epitaxial CuMnAs – tetragonal, collinear AFM
- From spin-orbit based reorientation switching to quench switching of AFM
- Quench switching - strong GMR like signals (20% at RT, 100% at low T)
- Electrical Quench switching with pulses down to ns range
- Optical switching with 120fs laser pulses

Atomically sharp domain walls in CuMnAs

- Invisible domain walls in PEEM images
- Observation of atomically sharp domain walls by DPC-STEM

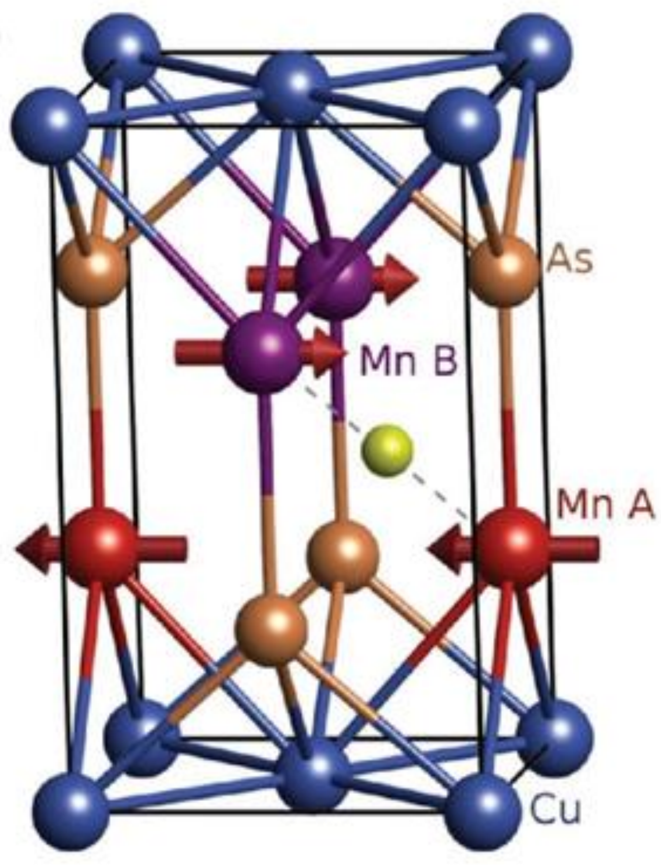
Temperature dependent relaxation

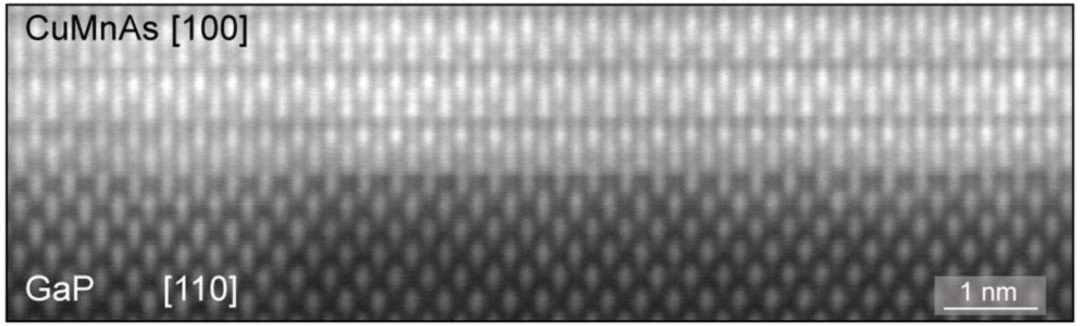
- Deterministic temperature dependent relaxation described by stretched exponentials

Functionality

- Write, read, erase functionality in a simple bar device
- Complex multilevel behaviour e.g. for Neuromorphic applications

Tetragonal antiferromagnetic CuMnAs



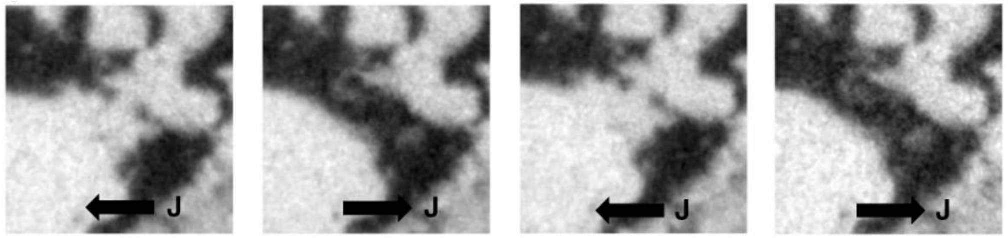


MBE growth on GaP (or GaAs, Si) substrates
Typical thickness 50nm

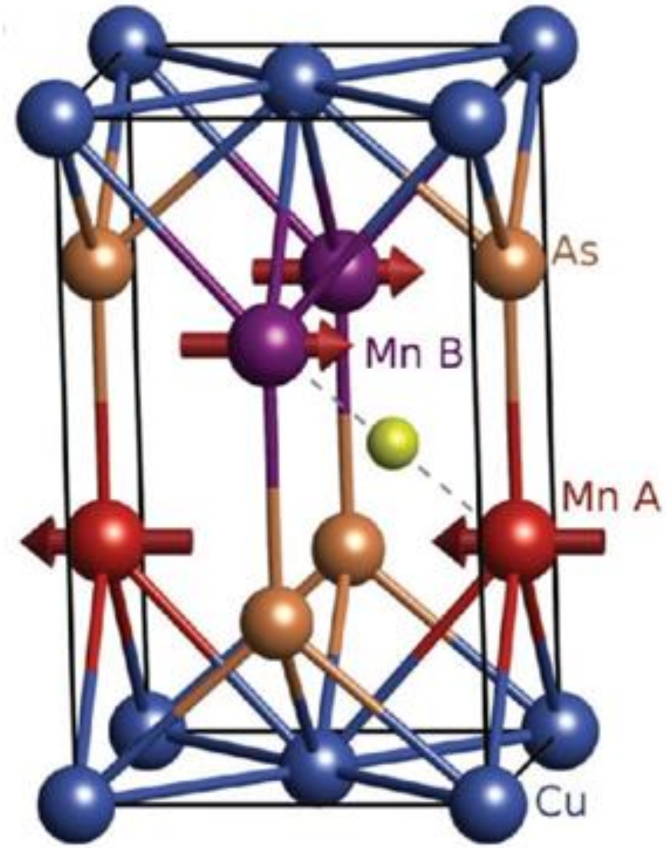
Collinear antiferromagnet with in-plane easy direction
T_N = 480K

From reorientation to quench switching

Reorientation of L vector using staggered SO fields
Present in CuMnAs due to special symmetry
(inversion symmetry broken by magnetic order)



Reorientation observed by XMLD-PEEM
AMR electrical readout, signal amplitude ~0.1%



Zelezny et al., PRL 2014
Wadley et al., Science 2016
Wadley et al., Nature Nanotech. 2018

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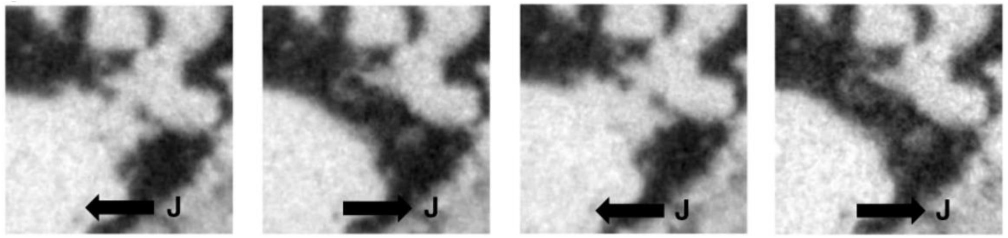

Reorientation observed by XMLD-PEEM
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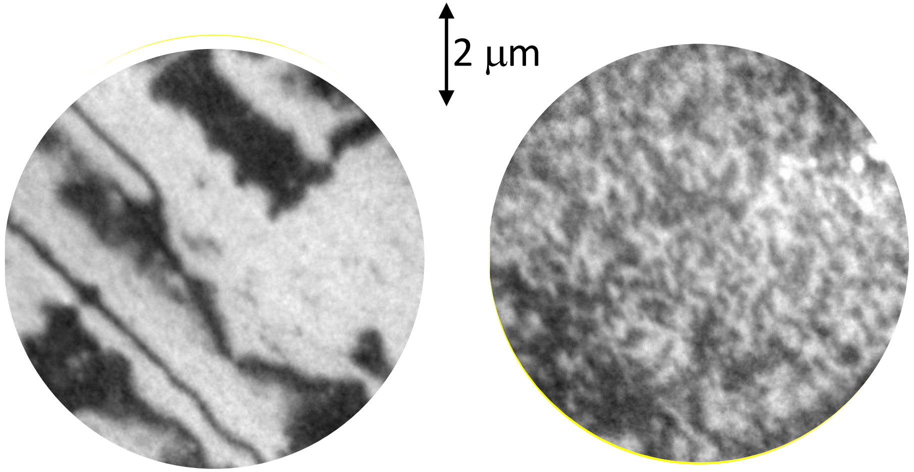
Strong pulses – large resistivity changes

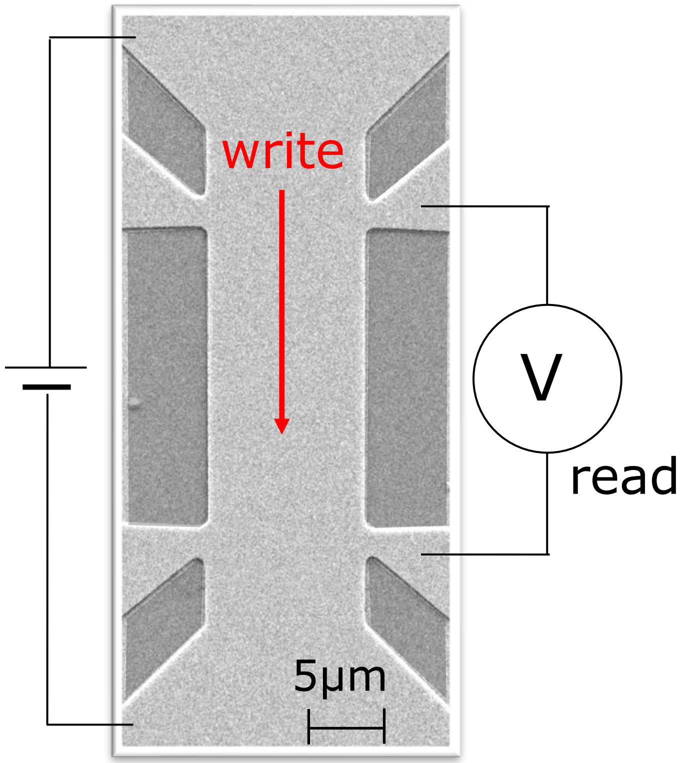


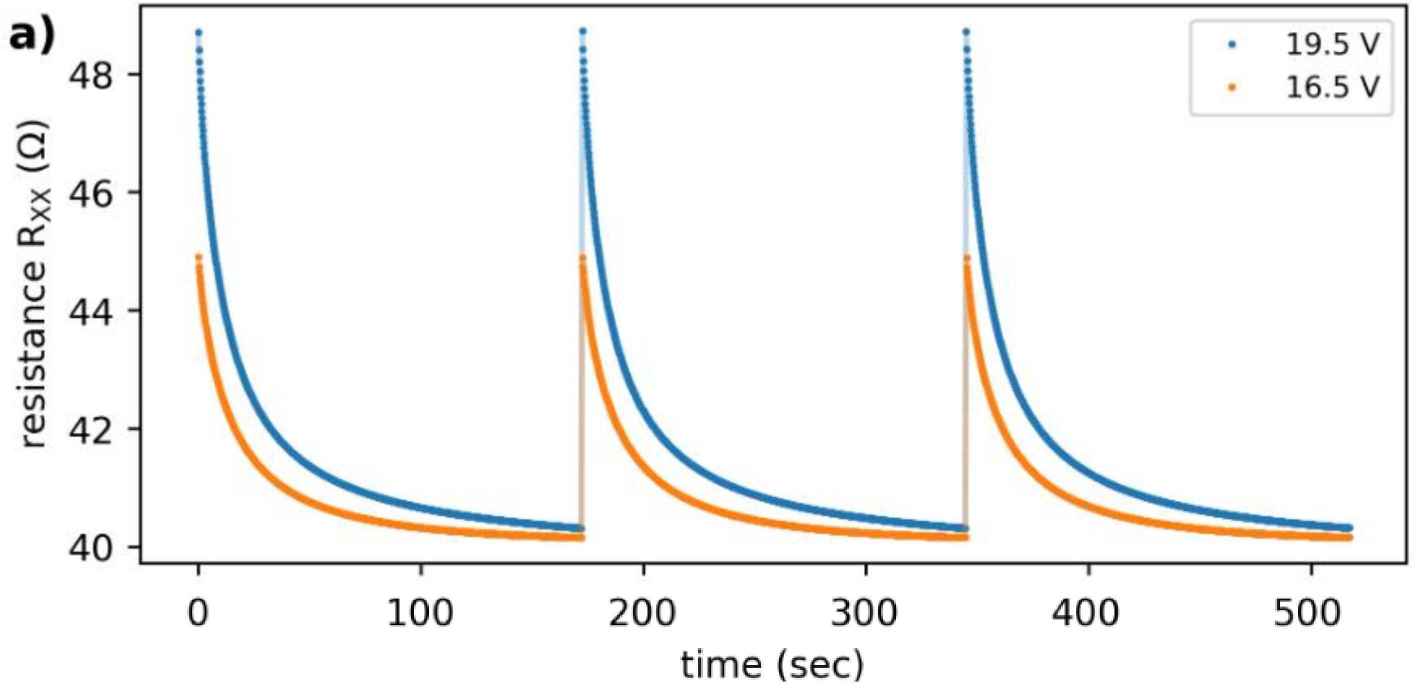
Quench-switching to metastable nano-textured magnetic state

Zelezny et al., PRL 2014
Wadley et al., Science 2016
Wadley et al., Nature Nanotech. 2018

Kaspar et al., Nature Electron (2020)

Quench switching of resistivity

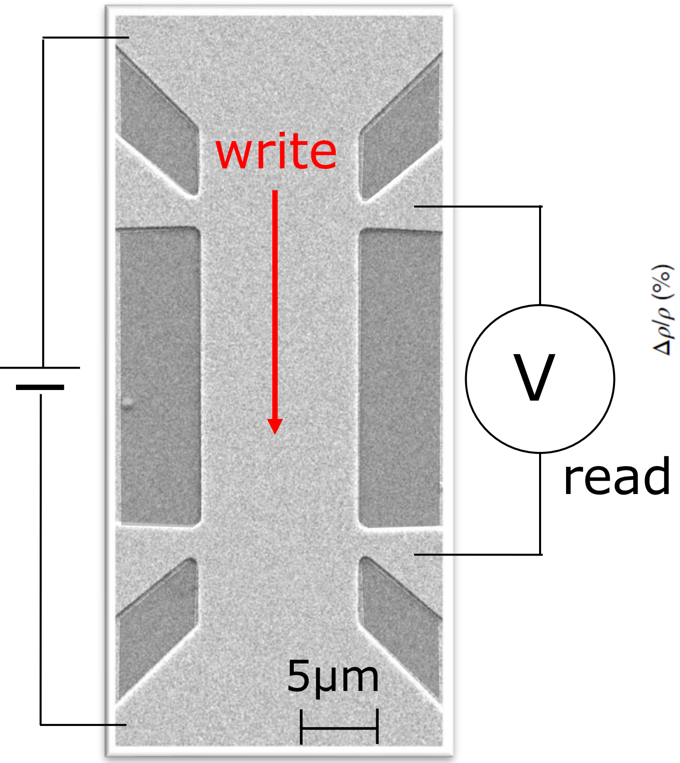




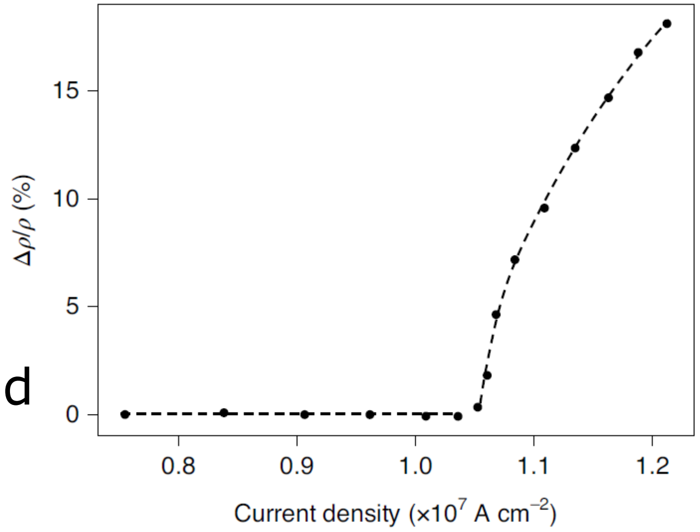
Maximum resistance change 20% at RT

Kaspar, PhD. ThesisElectron (2021)

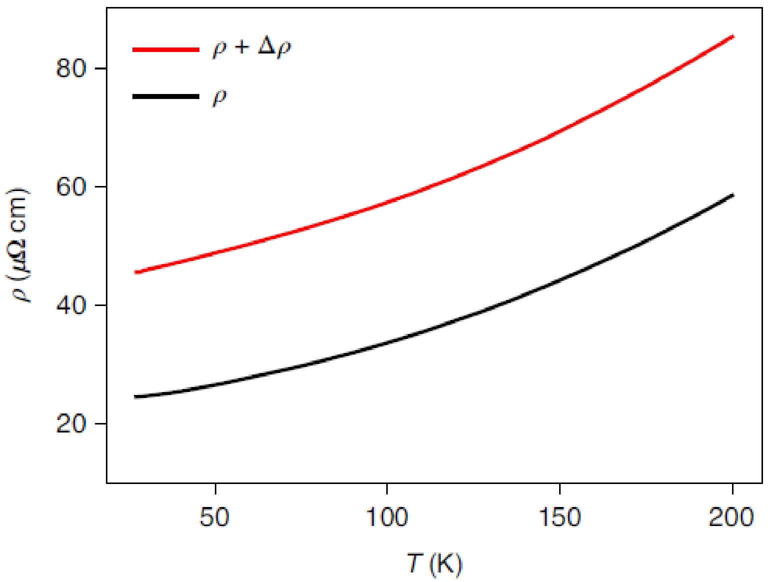
Amplitude of quench switching signal



Write pulse amplitude



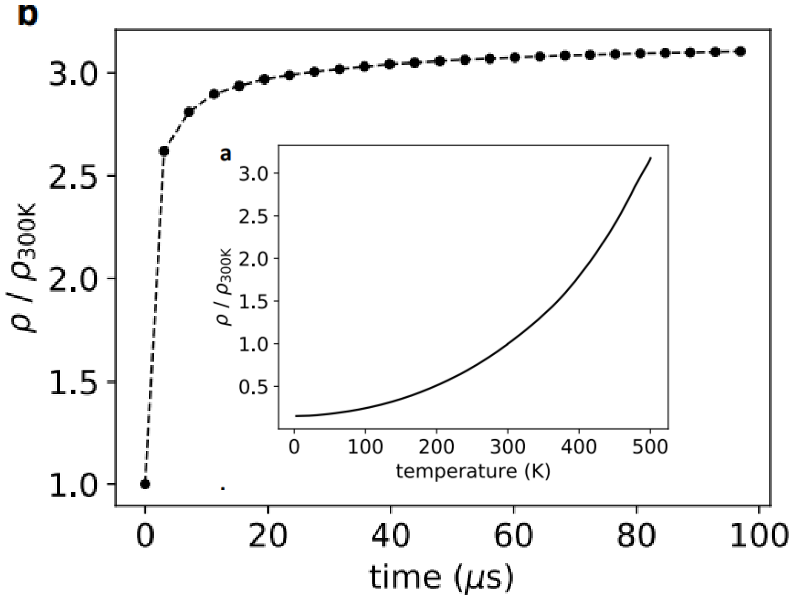
100% at low temperatures



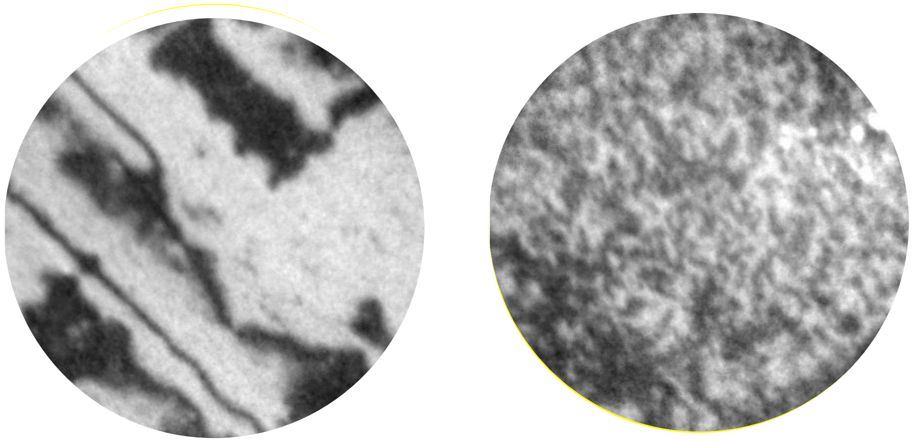
resistivity increase at low T corresponds to ab initio calculations of frozen random paramagnetic state - ***Máca, et al., PRB 96, 094406 (2017)***

Mechanism of quench switching

Resistivity during 100 μs writing electrical pulse

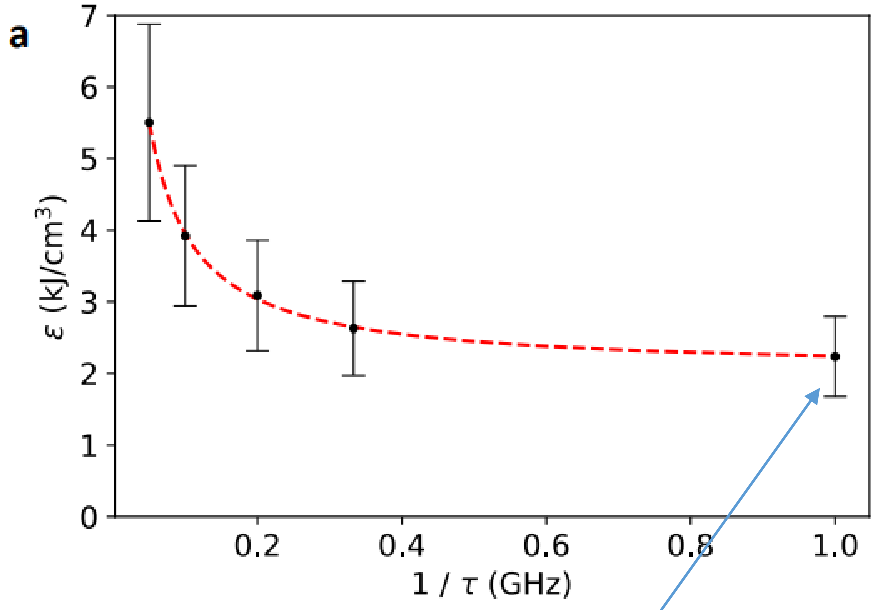


Temperature reaches during pulse T_N
Follows fast cooling – quench of disordered state



Short electrical and laser pulses

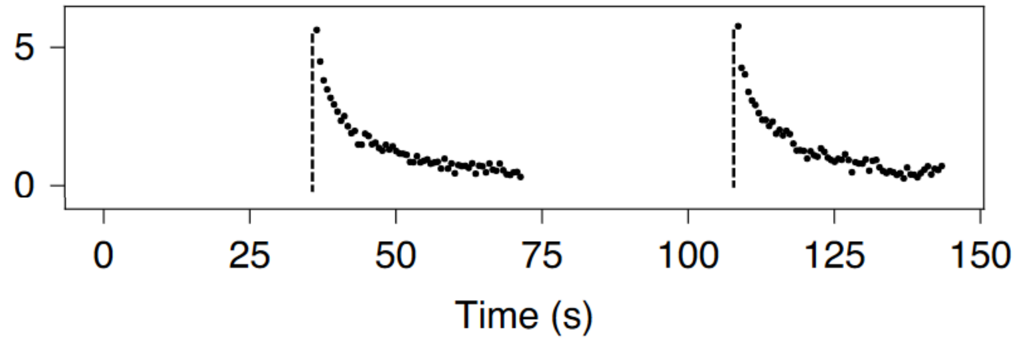
ns electrical pulses



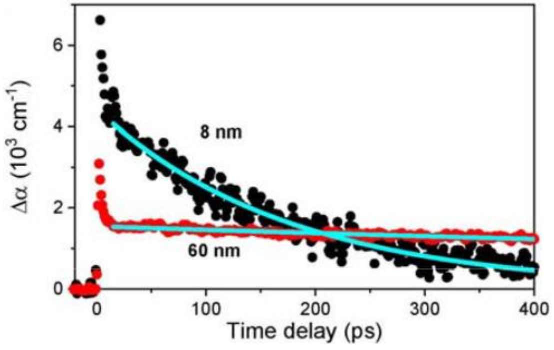
Energy needed to reach TN
(no time for heat dissipation)

100fs laser pulses

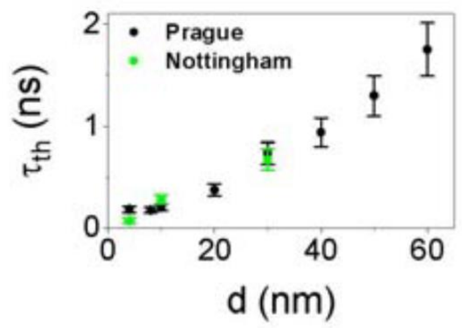
Absorbed energy density 2.6 kJ/cm^3



Optical detection of quench switching also possible



Cooling after pulse
(P&P experiement)



Surynek et al. JAP (2020)

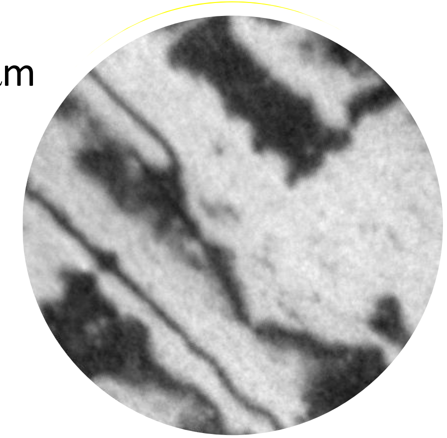
Magnetic imaging of nano-fragmentation in CuMnAs

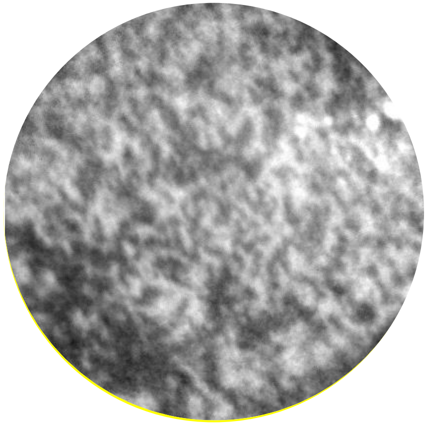
Before switching

Quenching into
nano-textured state

XMLD-PEEM

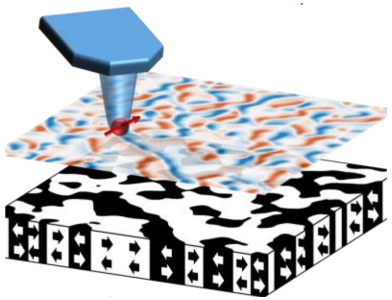
2 μm



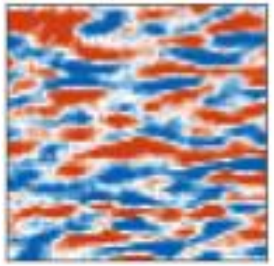


Kaspar et al., Nature Electron. (2020)

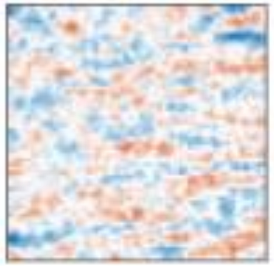
NV-diamond

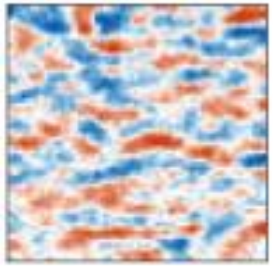


Relaxed
towards large domains



1 μm

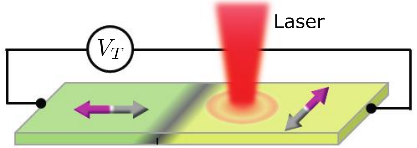




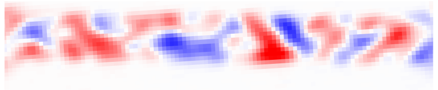
3 days

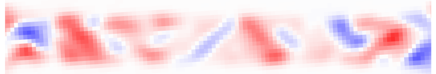
Wornle, KO et al., arXiv (2019)

Magneto-Seebeck



5 μm





1 week

Janda, KO et al., Phys. Rev. Mat. (2020)

Magnetic imaging of nano-fragmentation in CuMnAs

Micromagnetic DW width 100nm

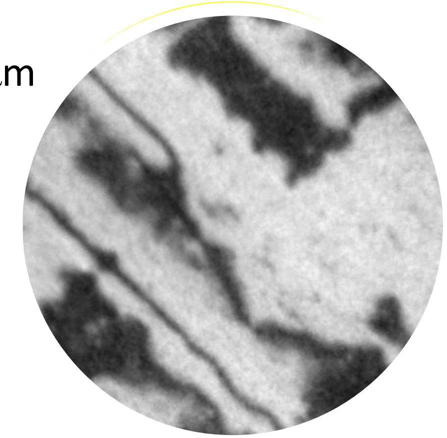
Feature size below ~10nm resolution

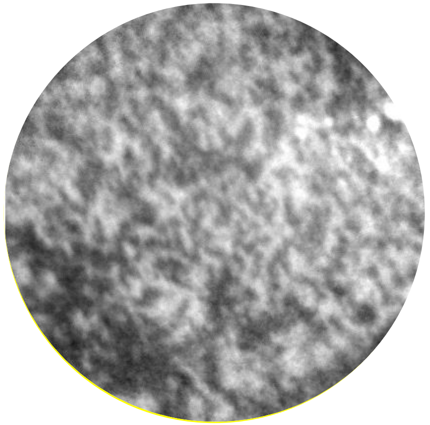
Before switching

Quenching into nano-textured state

XMLD-PEEM

2 μm





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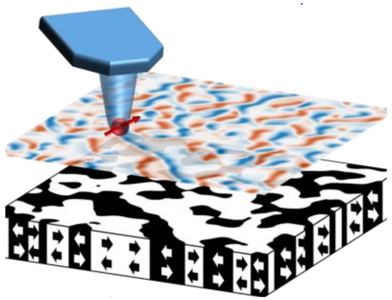
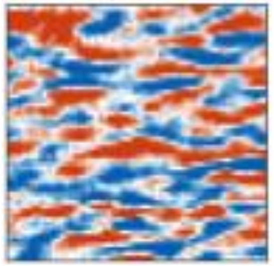
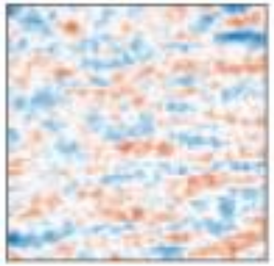
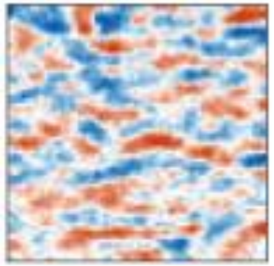


Relaxed towards large domains

1 μm







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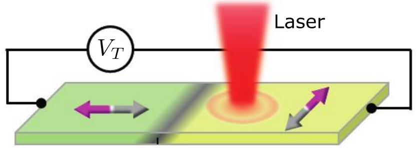

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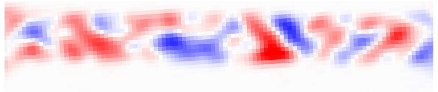

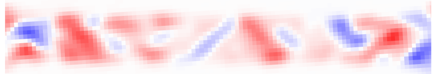

1 week

Janda, KO et al., Phys. Rev. Mat. (2020)

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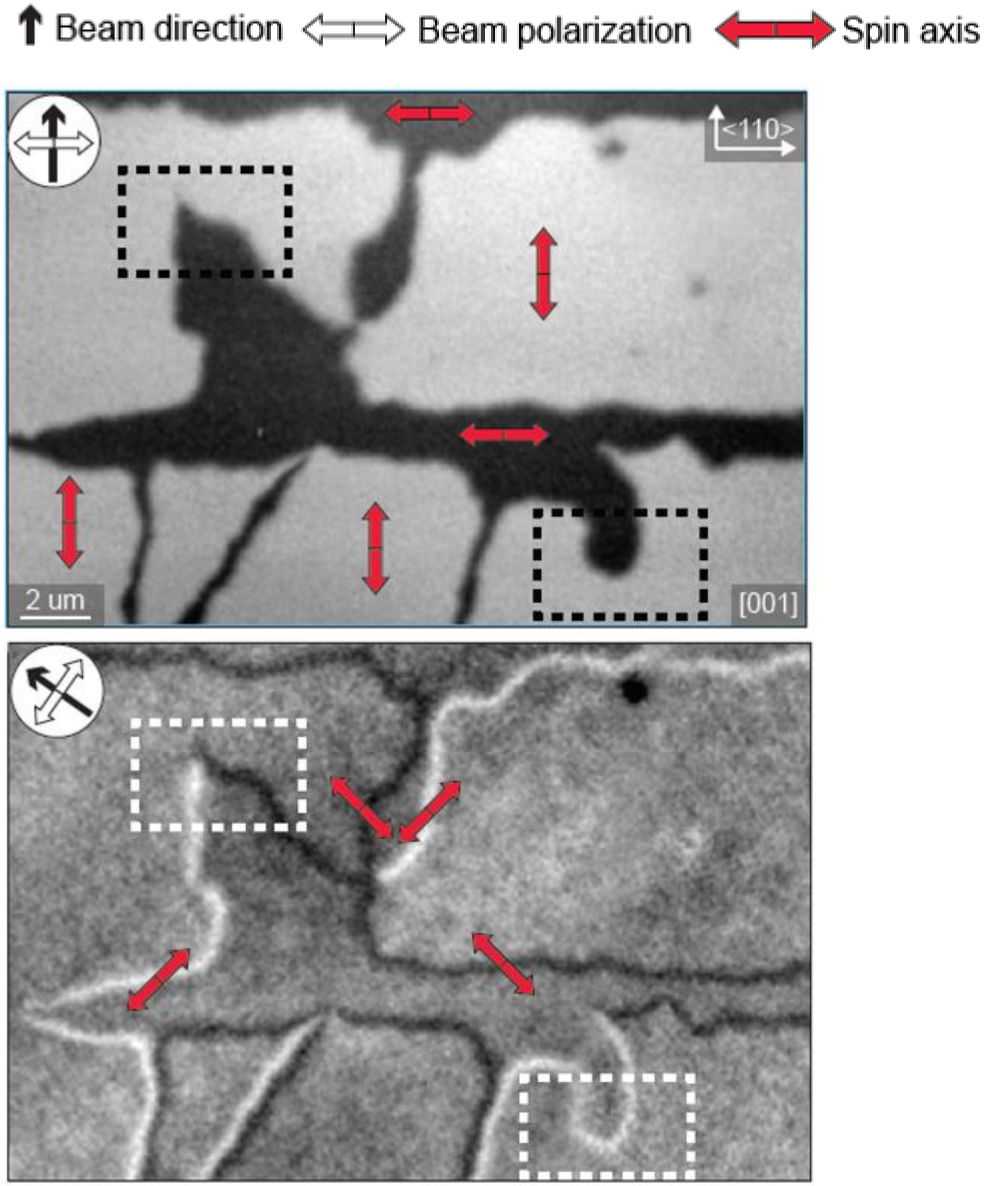
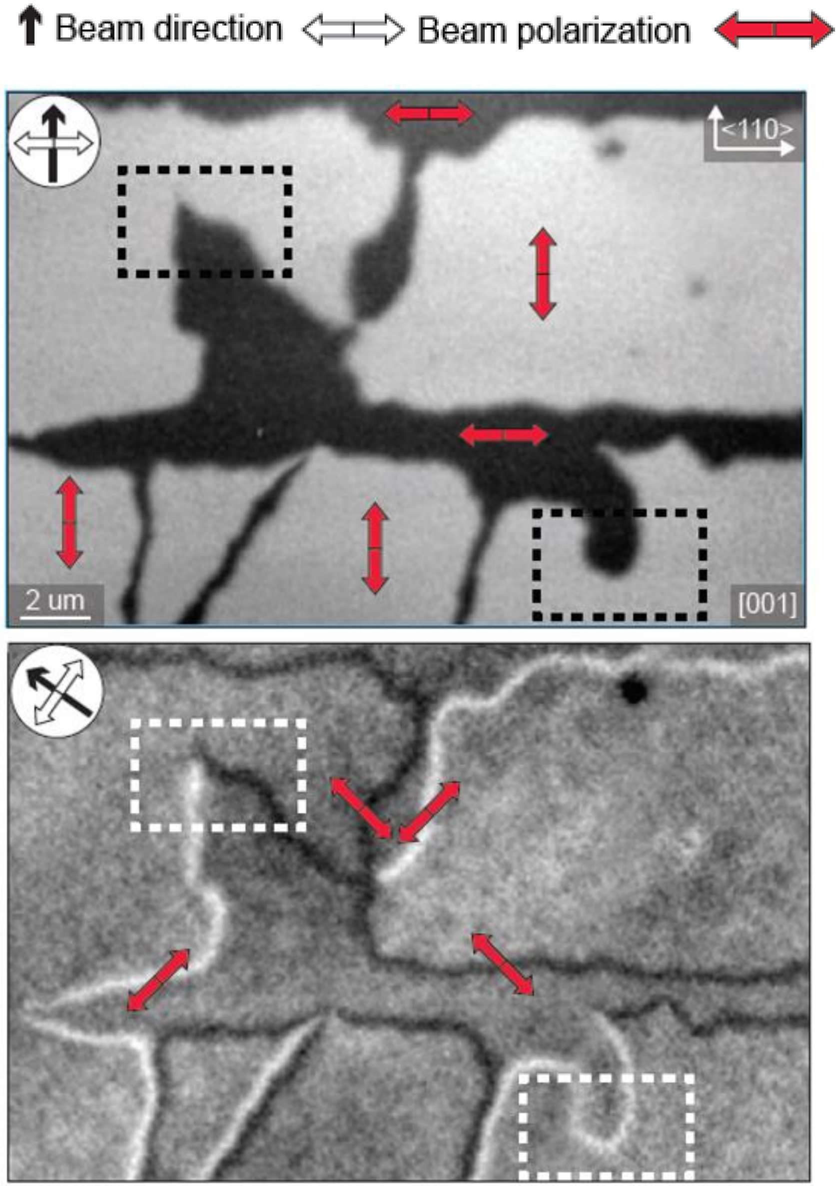
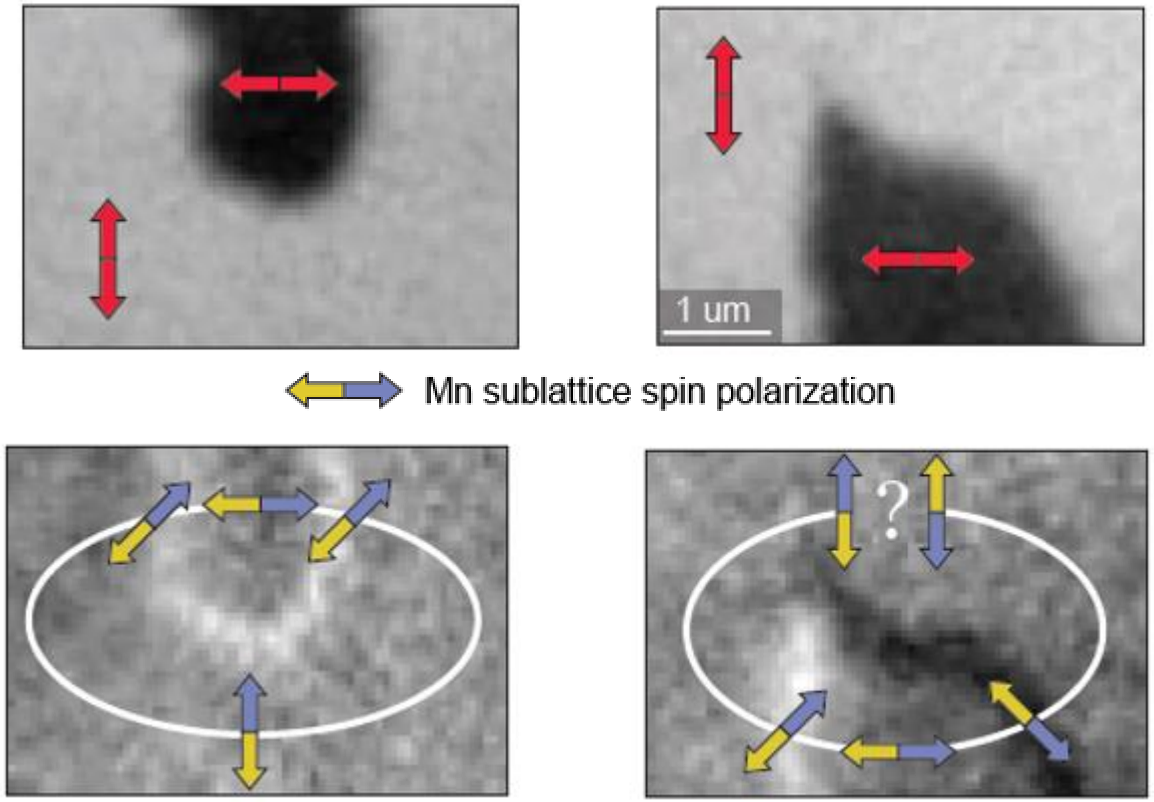
More PEEM imaging



Krizek, KO et al., arXiv (2020)

More PEEM imaging





Micromagnetic 90° DWs
w_{DW} = 100nm

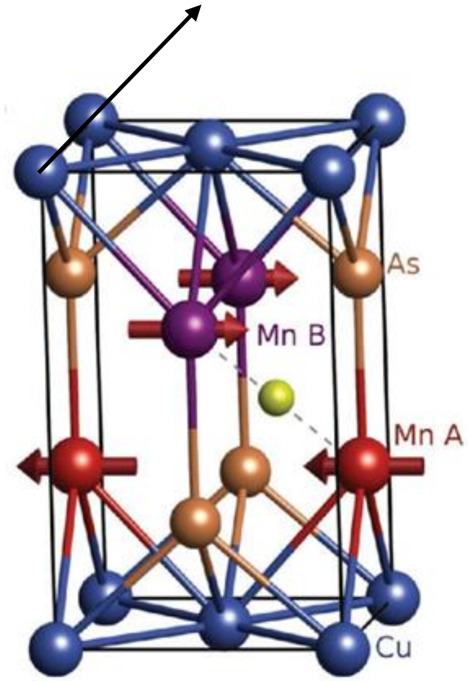
Invisible 180° DWs
$w_{DW} \leq$ 10nm

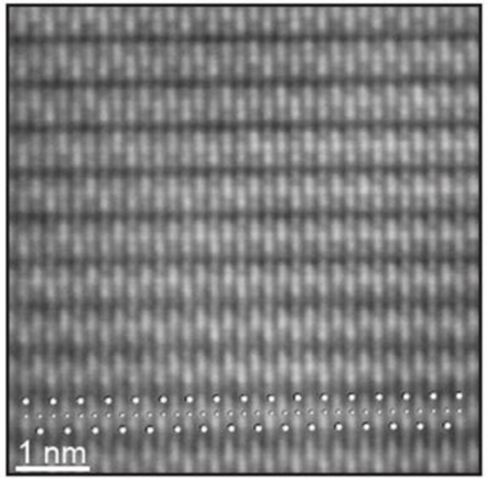
Krizek, KO et al., arXiv (2020)

Atomically sharp DWs in DPC-STEM

Krizek et al., arXiv (2020)

Electron beam
[100]





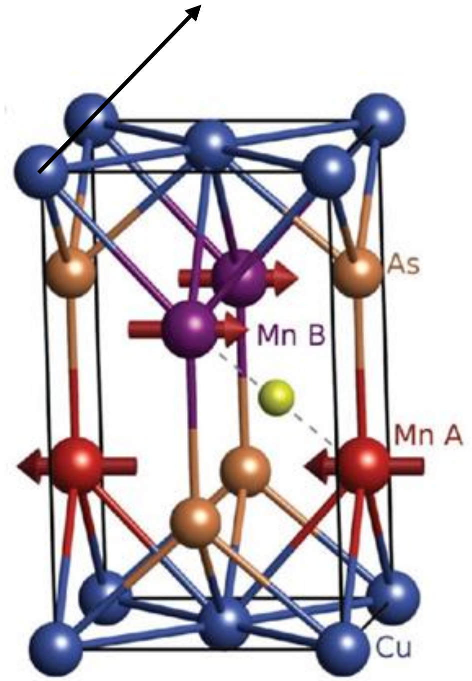
50-100nm lamella
Column of ~100 atoms

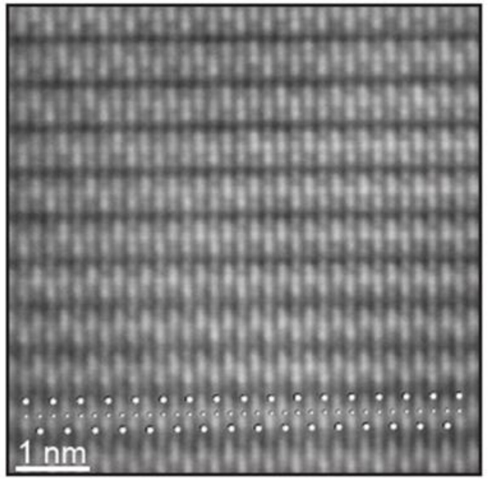
HAADF Detector … electrons scattered by the column of atoms
(High Angle Annular Dark Field)

Atomically sharp DWs in DPC-STEM

Krizek et al., arXiv (2020)

Electron beam
[100]





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HAADF Detector … electrons scattered by the column of atoms
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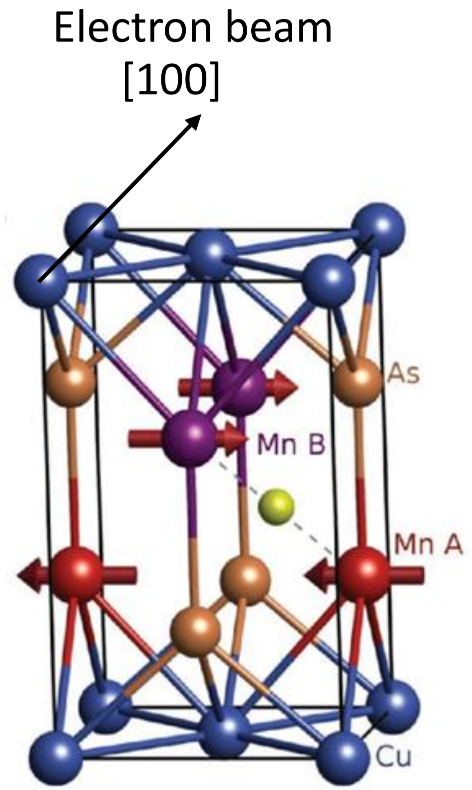
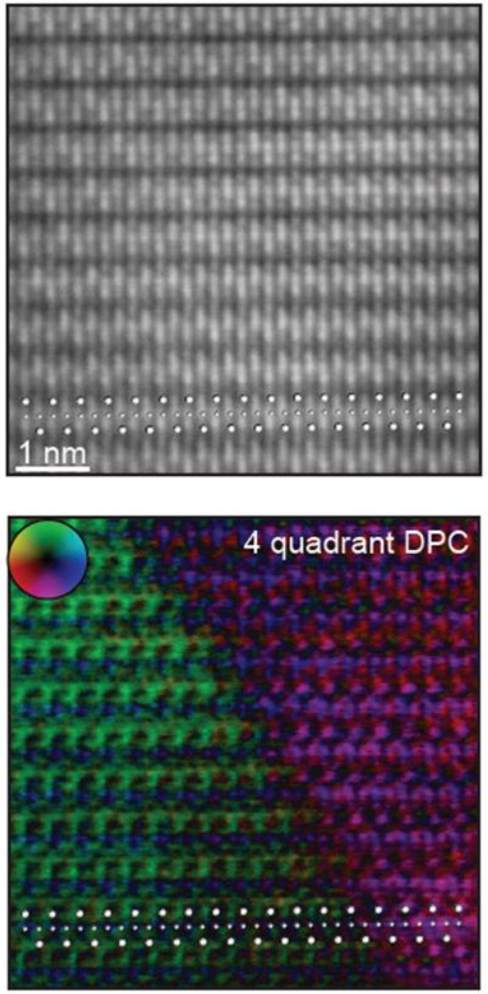
DPC Detector … angular deviation of passing electrons
(Differential Phase Contrast) -> magnetic contrast on FM domains

All atoms in the column/plane has the same polarization

Atomically sharp DWs in DPC-STEM

Krizek et al., Sci. Adv. (2022)





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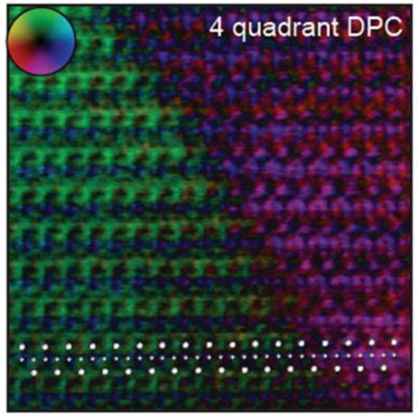
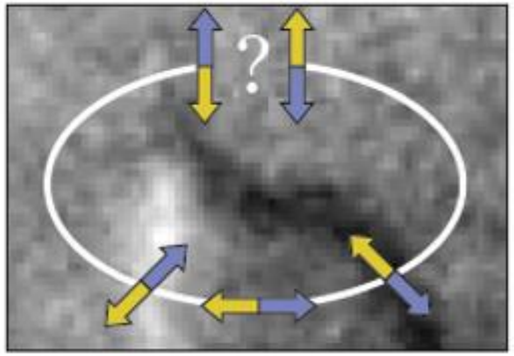
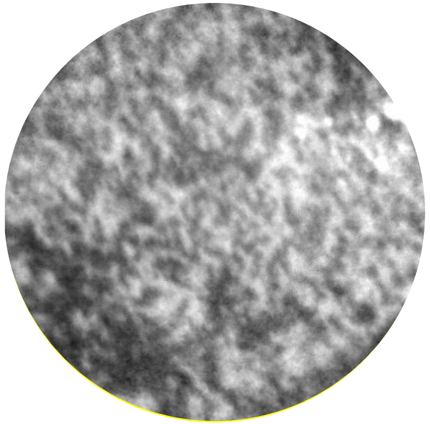
Carefully excluded origin due to possible artefacts (abruptly varying strain, chemical composition, lamella thickness, crystal rotation, and formation of crystal grain overlaps)

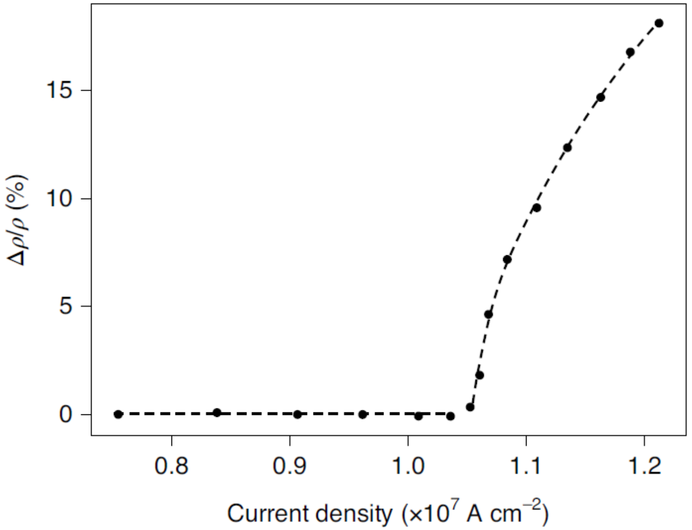
Dynamic diffraction calculations consistent with the observed contrast

Atomically sharp domain walls









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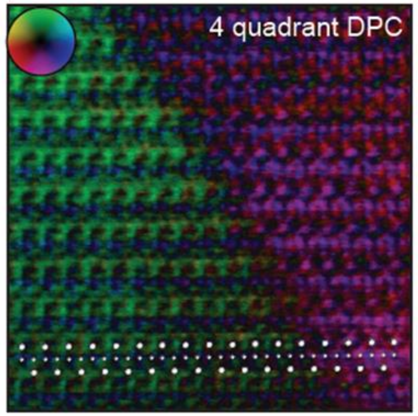
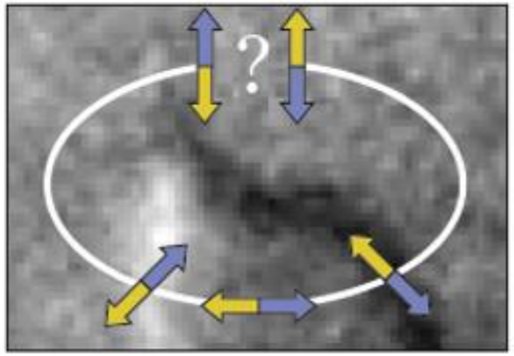
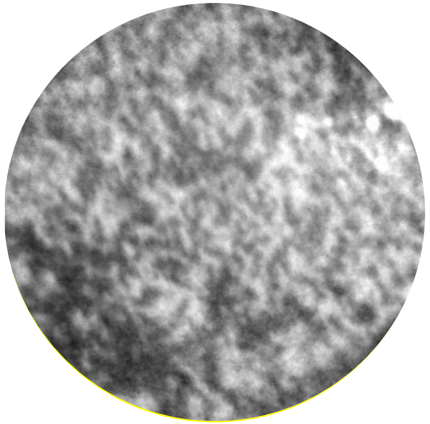
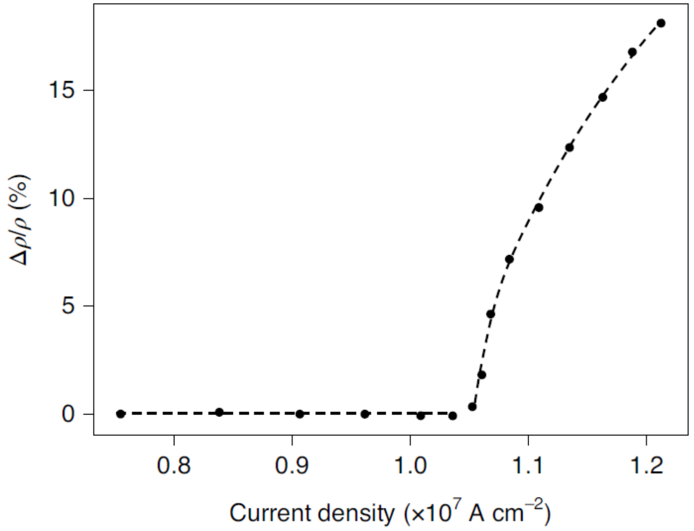
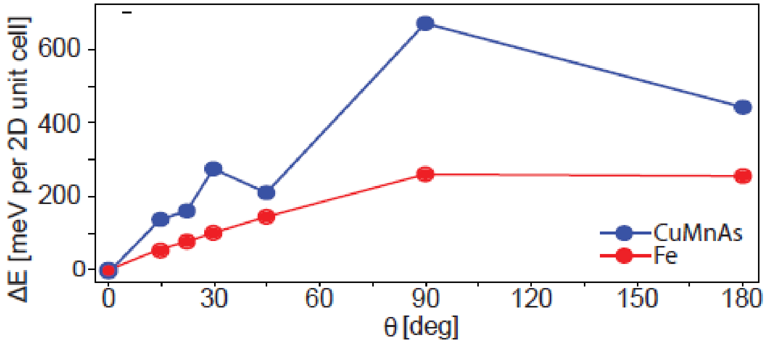








Ab-initio calculations of sharp domain walls



- Deviation from micromagnetic semiclassical exchange constant model
- Metastable magnetic configurations – enough to stabilise metastable quenched state
- In FMs obscured by long range dipolar interaction – quenching ineffective

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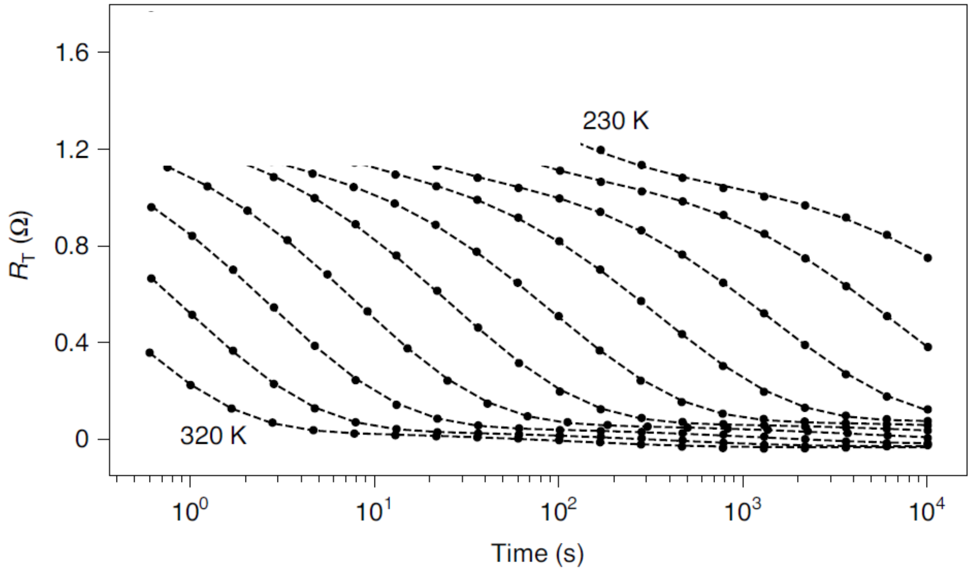
Thermally activated relaxation – two main components



Relaxation well characterised by stretched exponential function :

$$R(t) = R_0 + \Delta R \cdot e^{-\left(\frac{t}{\tau}\right)^{3/5}}$$

Exponent 3 / 5 -> in complex interacting 3D system

Phillips J. Non-cryst. Sol. ,2006

Kaspar, KO et al., Nature Electron (2020)

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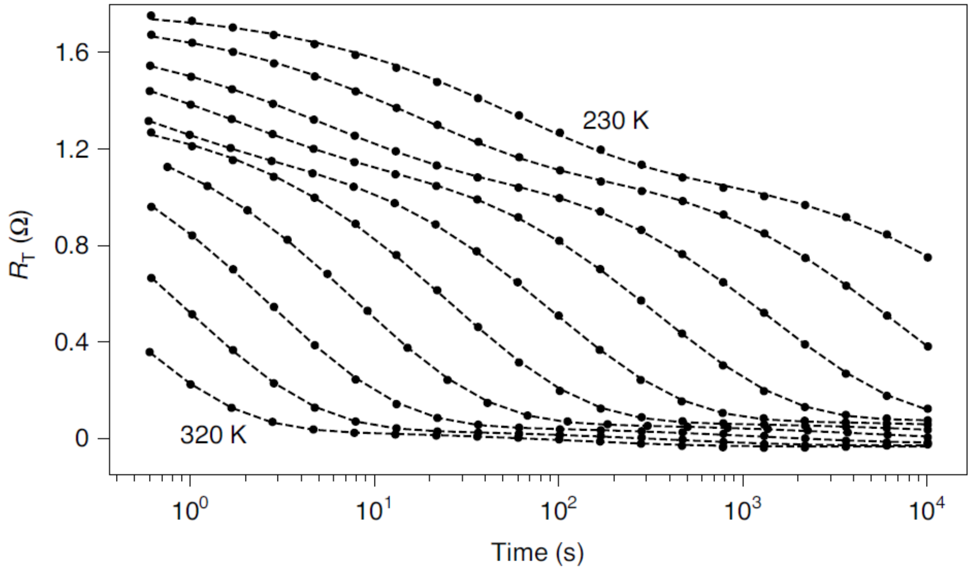

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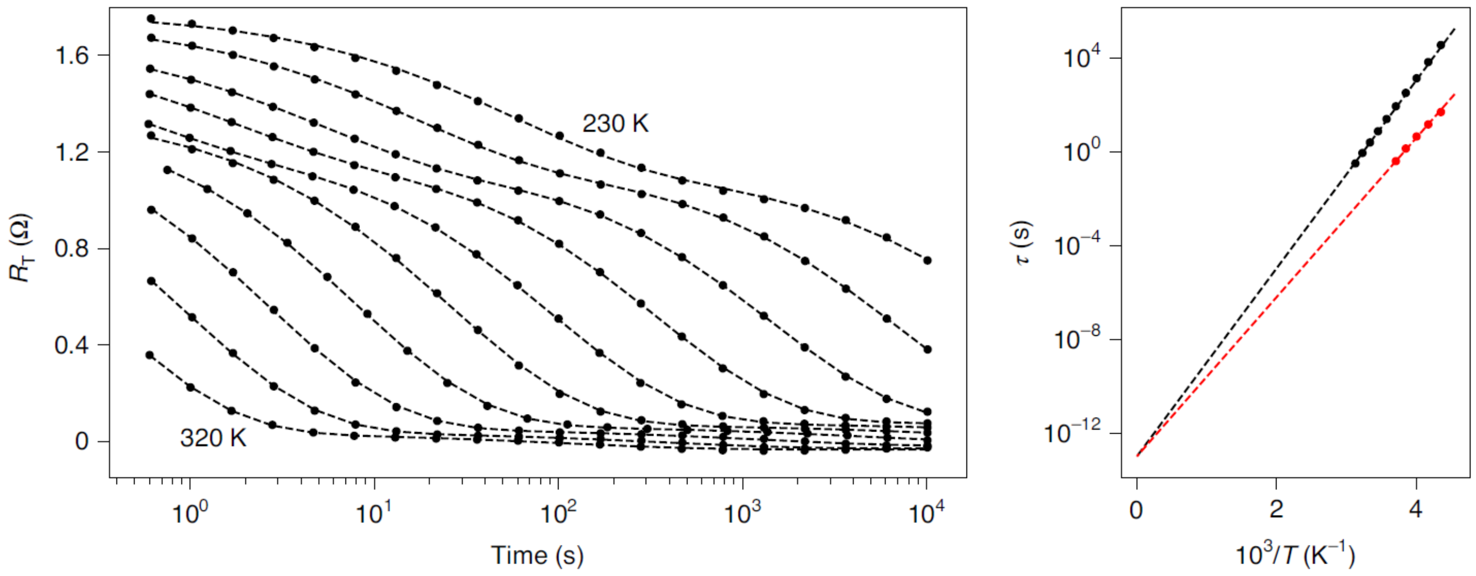


$$\tau = \tau_0 \cdot e^{\frac{E_A}{k_B T}}$$

Two main components:

10s and 10ms at RT

Activation energy

E_{A1}/kB = 30.8 × 300 K

E_{A2}/kB = 26.1 × 300 K

Relaxation well characterised by stretched exponential function :

$$R(t) = R_0 + \Delta R \cdot e^{-\left(\frac{t}{\tau}\right)^{3/5}}$$

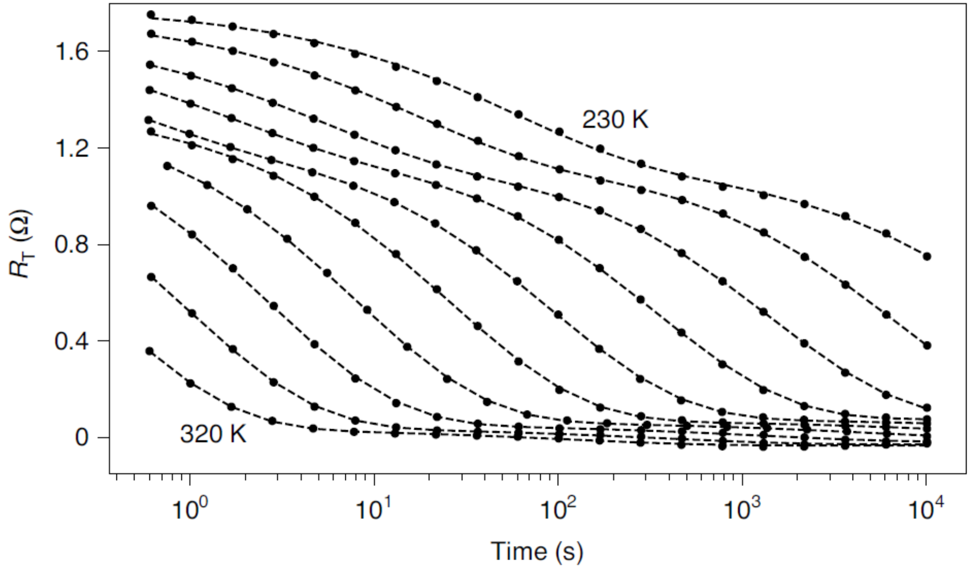
1 / τ_0 in THz range -> antiferromagnetic dynamics

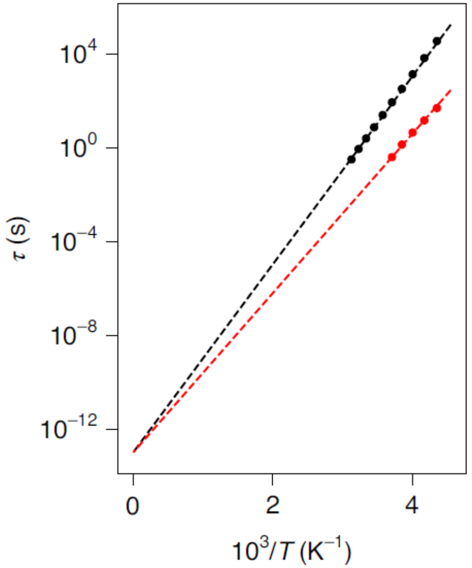
Exponent 3 / 5 -> in complex interacting 3D system

Phillips J. Non-cryst. Sol. ,2006

Kaspar, KO et al., Nature Electron (2020)

Thermally activated relaxation – two main components





$$\tau = \tau_0 \cdot e^{\frac{E_A}{k_B T}}$$

Two main components:

10s and 10ms at RT

Activation energy

E_{A1}/kB = 30.8 × 300 K

E_{A2}/kB = 26.1 × 300 K

Relaxation well characterised by stretched exponential function :

$$R(t) = R_0 + \Delta R \cdot e^{-\left(\frac{t}{\tau}\right)^{3/5}}$$

1 / τ_0 in THz range -> antiferromagnetic dynamics

ULTRAFAST relaxation

Exponent 3 / 5 -> in complex interacting 3D system

Phillips J. Non-cryst. Sol. ,2006

Kaspar, KO et al., Nature Electron (2020)

Outline

Quench switching of magnetic state in CuMnAs

- Epitaxial CuMnAs – tetragonal, collinear AFM
- From spin-orbit based reorientation switching to quench switching of AFM
- Quench switching - strong GMR like signals (20% at RT, 100% at low T)
- Electrical Quench switching with pulses down to ns range
- Optical switching with 120fs laser pulses

Atomically sharp domain walls in CuMnAs

- Invisible domain walls in PEEM images
- Observation of atomically sharp domain walls by DPC-STEM

Temperature dependent relaxation

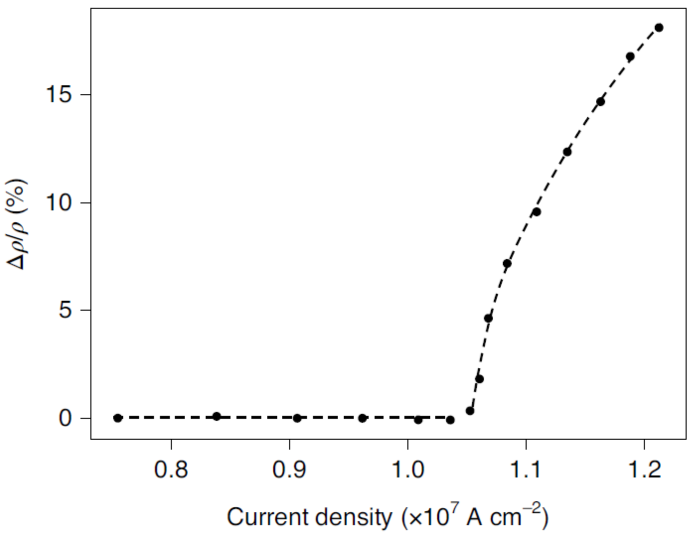
- Deterministic temperature dependent relaxation described by stretched exponentials

Functionality

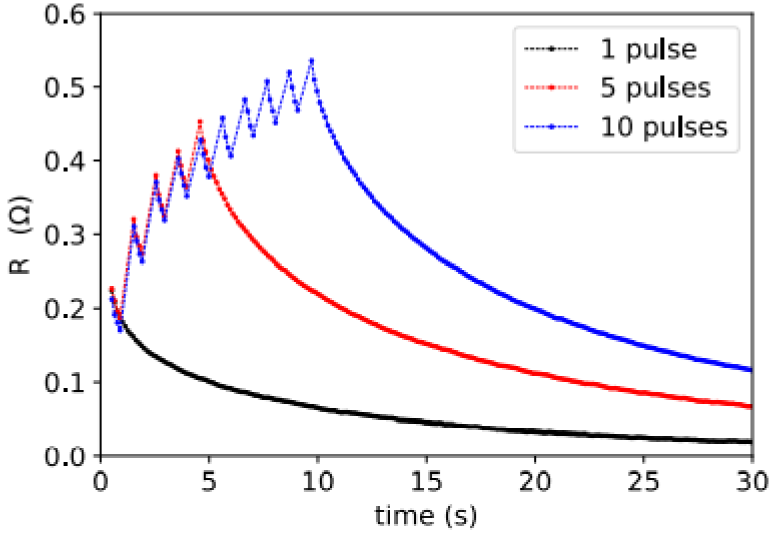
- **Write, read, erase functionality in a simple bar device**
- **Complex multilevel behaviour e.g. for Neuromorphic applications**

Multilevel character of quench switching

Strength of writing pulse



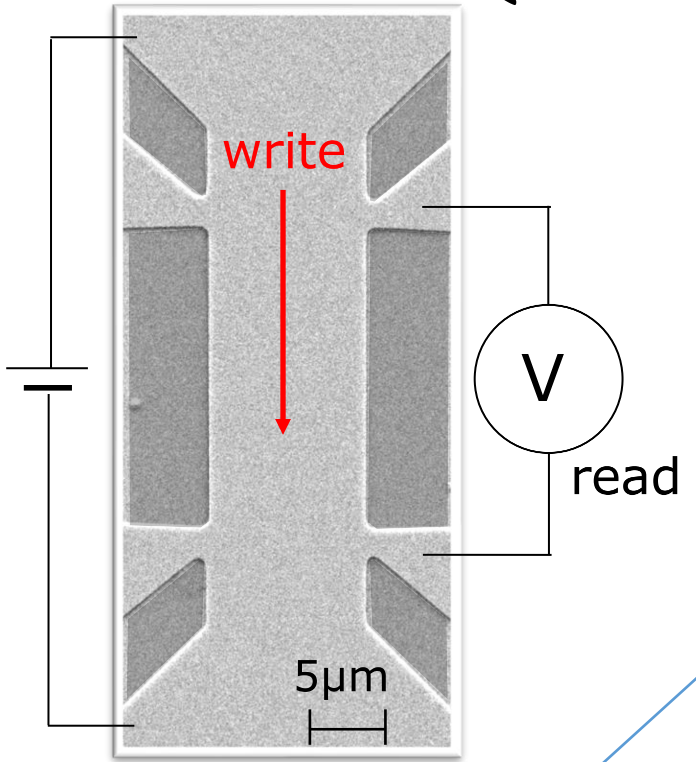
Pulse counter functionality

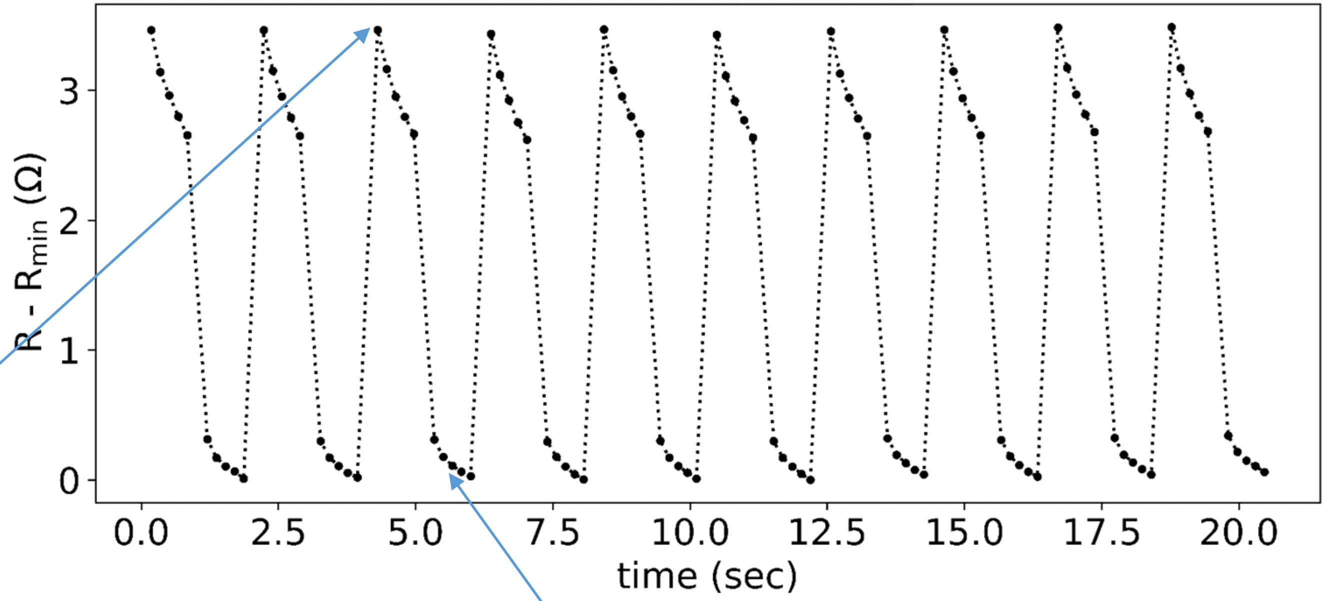


1ns pulses

Kaspar, KO et al., Nature Electron (2020)

Quench-switching / erasing experiment



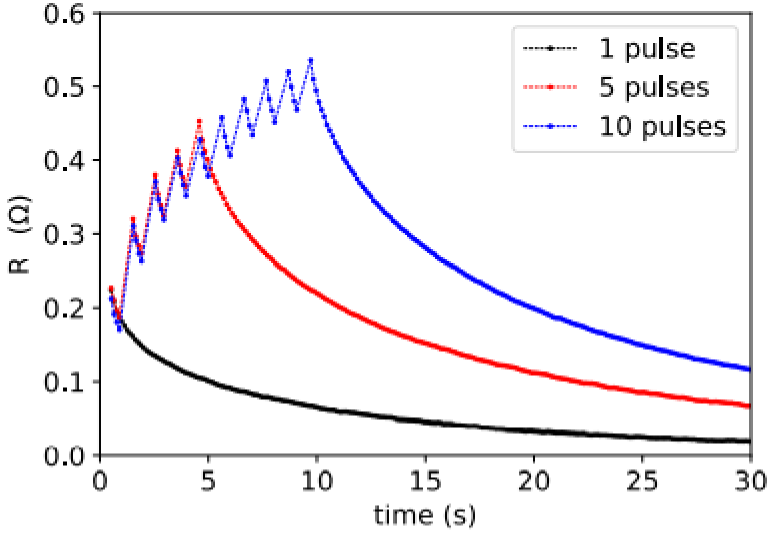


High current density
- high peak temperature
- quenching of strongly fragmented state

Lower current density
- lower peak temperature
- acceleration of thermally activated relaxation

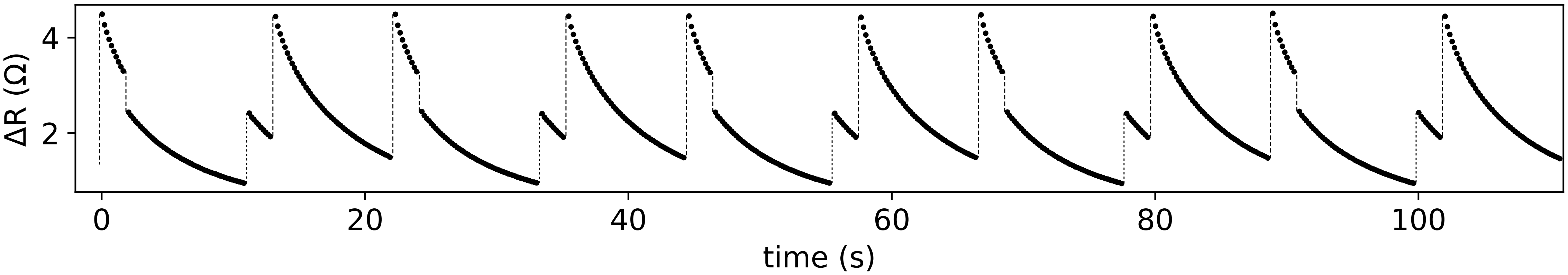
Kaspar, KO et al., Nature Electron (2020)

Potential for neuromorphic computation



Multilevel - analogue memory (synapses)

Response depend on number, delay, order of pulses (neuron)



Kaspar, KO et al., Nature Electron (2020)

List of co-authors:

Kaspar, KO et al., Nature Electron (2020)

Quenching of an antiferromagnet into high resistivity states using electrical or ultrashort optical pulses

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Křížek et al, Sci. Adv. (2022)

Atomically sharp domain walls in an antiferromagnet

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Thank you for your attention