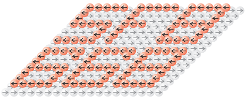


Funded by the Horizon2020 Framework Programme of the European Union

Various ways to tune non-collinear magnetism in ultrathin films

Aurore Finco, Pin-Jui Hsu, Levente Rózsa, Niklas Romming, Elena Vedmedenko, André Kubetzka, Kirsten von Bergmann and Roland Wiesendanger

University of Hamburg

Non-collinear magnetic textures in ultrathin films

(spin spirals, skyrmions, ...)

Competition between:

- Dipolar interactions
- Exchange interactions
- Dzyaloshinskii-Moriya interaction
- Magnetic anisotropy
- Higher order interactions

Non-collinear magnetic textures in ultrathin films

(spin spirals, skyrmions, ...)

Competition between:

- Dipolar interactions
- Exchange interactions
- Dzyaloshinskii-Moriya interaction
- Magnetic anisotropy
- Higher order interactions

Length scale

Non-collinear magnetic textures in ultrathin films

(spin spirals, skyrmions, ...)

Chirality

Thermal stability

Topology

Competition between:

- Dipolar interactions
- Exchange interactions
- Dzyaloshinskii-Moriya interaction
- Magnetic anisotropy
- Higher order interactions

Hydrogenation

Temperature

Length scale

Non-collinear magnetic textures in ultrathin films

(spin spirals, skyrmions, ...)

Chirality

Choice of the interface

Thermal stability

Film thickness

Topology

Magnetic field

Competition between:

- Dipolar interactions
- Exchange interactions
- Dzyaloshinskii-Moriya interaction
- Magnetic anisotropy
- Higher order interactions

Non-collinear magnetic textures in ultrathin films

(spin spirals, skyrmions, ...)

Epitaxial strain

Hydrogenation

Temperature

Length scale

Thermal stability

Film thickness

Chirality

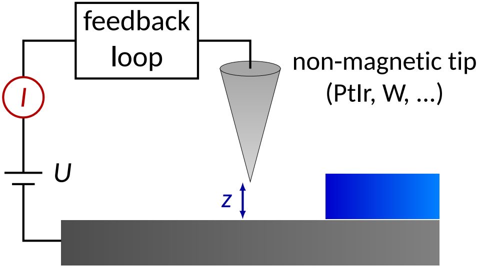
Choice of the interface

Topology

Magnetic field

Electric field

Scanning tunneling microscopy

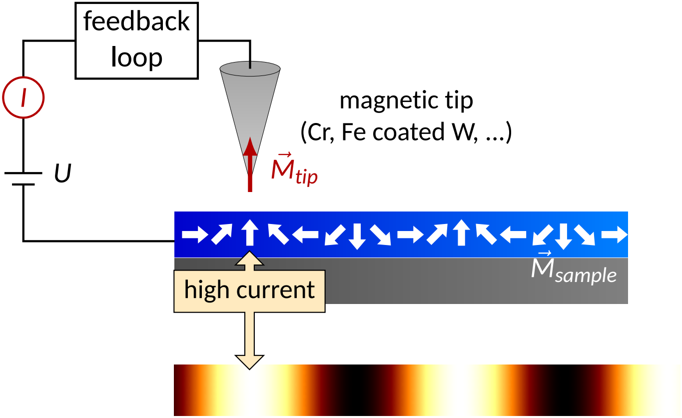


$$I \propto U e^{-\kappa z}$$

- Feedback loop to keep the current constant and measure the topography of the surface
- Measurement of the differential conductance $\frac{\mathrm{d}I}{\mathrm{d}U}$ using lock-in technique
- $\frac{\mathrm{d}I}{\mathrm{d}U}$ gives access to the local density of states

Spin-polarized STM

Tunneling MagnetoResistance

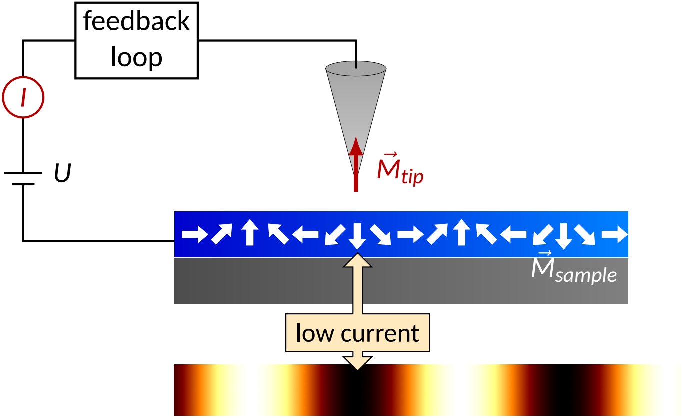


$$I = I_0 \left(1 + P_{sample} P_{tip} \cos(\vec{M}_{sample}, \vec{M}_{tip})\right)$$

R. Wiesendanger. Spin mapping at the nanoscale and atomic scale. *Reviews of Modern Physics* 81 (2009), 1495–1550.

Spin-polarized STM

Tunneling MagnetoResistance

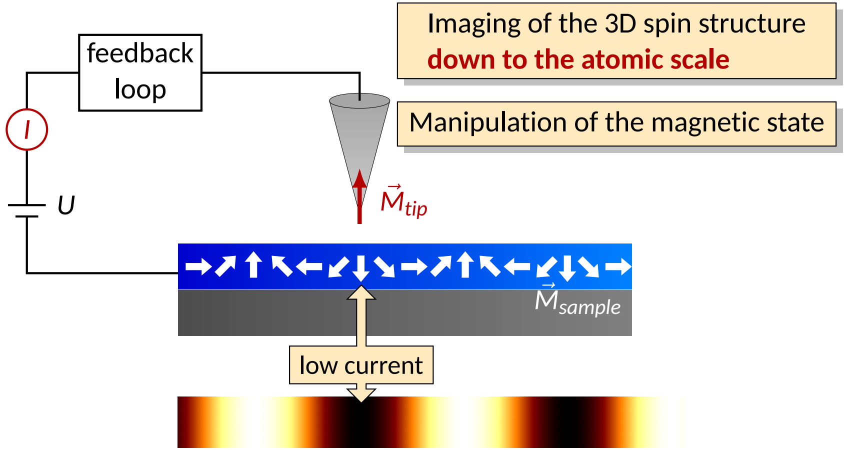


$$I = I_0 \left(1 + P_{sample} P_{tip} \cos(\vec{M}_{sample}, \vec{M}_{tip})\right)$$

R. Wiesendanger. Spin mapping at the nanoscale and atomic scale. *Reviews of Modern Physics* 81 (2009), 1495–1550.

Spin-polarized STM

Tunneling MagnetoResistance

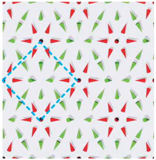


$$I = I_0 \left(1 + P_{sample} P_{tip} \cos(\vec{M}_{sample}, \vec{M}_{tip})\right)$$

R. Wiesendanger. Spin mapping at the nanoscale and atomic scale. *Reviews of Modern Physics* 81 (2009), 1495–1550.

The Fe/Ir interface

- Strong DMI, about 1.8 meV per atom.
  - Nanoskyrmion lattice in the monolayer Fe.

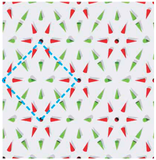


S. Heinze *et al.* Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nature Physics* 7.9 (2011), 713–718.

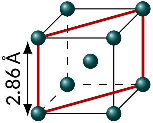
P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

The Fe/Ir interface

- Strong DMI, about 1.8 meV per atom.
  - Nanoskyrmion lattice in the monolayer Fe.

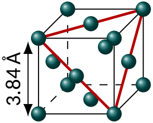


Bulk Fe: bcc



bcc(110) nearest neighbour distance: $a = 2.47\,\text{Å}$

Bulk Ir: fcc



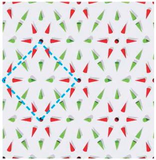
fcc(111) nearest neighbour distance: $a = 2.72\,\text{Å}$

S. Heinze *et al.* Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nature Physics* 7.9 (2011), 713–718.

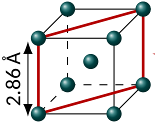
P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

The Fe/Ir interface

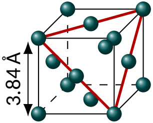
- Strong DMI, about 1.8 meV per atom.
  - Nanoskyrmion lattice in the monolayer Fe.



Bulk Fe: bcc



Bulk Ir: fcc



bcc(110) nearest neighbour distance: $a = 2.47$ Å

fcc(111) nearest neighbour distance: $a = 2.72$ Å

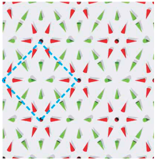
- Large strain on the Fe film.

S. Heinze *et al.* Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nature Physics* 7.9 (2011), 713–718.

P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

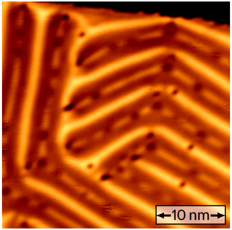
The Fe/Ir interface

- Strong DMI, about 1.8 meV per atom.
  - Nanoskyrmion lattice in the monolayer Fe.



bcc(110) nearest neighbour distance: $a = 2.47\,\text{Å}$

fcc(111) nearest neighbour distance: $a = 2.72\,\text{Å}$

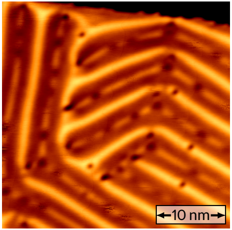


- Large strain on the Fe film.
  - Formation of dislocation lines when the thickness of the Fe film is larger than one atomic layer.

S. Heinze *et al.* Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nature Physics* 7.9 (2011), 713–718.

P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

The double layer Fe on Ir(111)

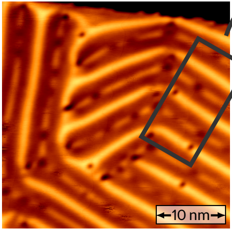


200 mV, 1 nA, 5 K, 0 T

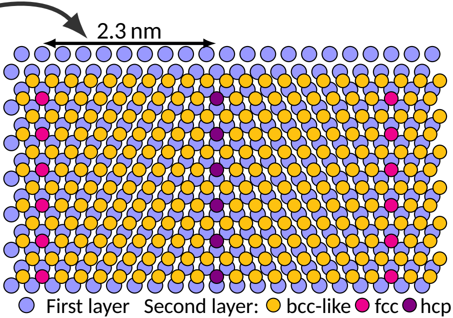
- Reconstruction lines along the 3 equivalent crystallographic directions
- Lines due to uniaxial strain release

P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

The double layer Fe on Ir(111)



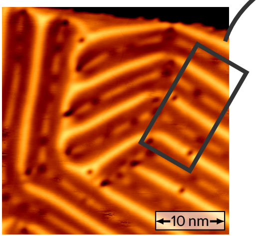
200 mV, 1 nA, 5 K, 0 T



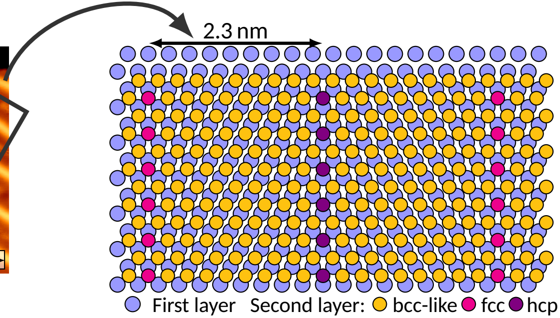
- Reconstruction lines along the 3 equivalent crystallographic directions
- Lines due to uniaxial strain release

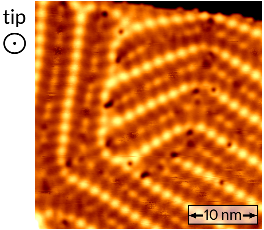
P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

The double layer Fe on Ir(111)



200 mV, 1 nA, 5 K, 0 T



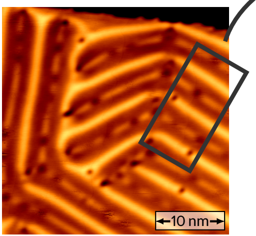


200 mV, 1 nA, 5 K, 4 T

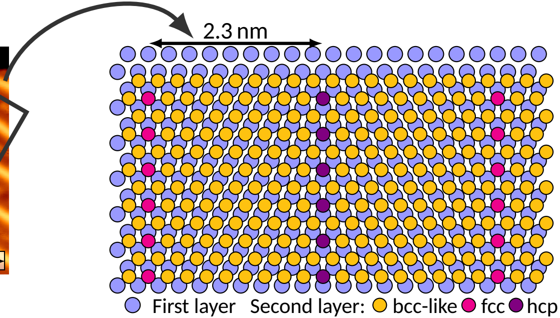
- Reconstruction lines along the 3 equivalent crystallographic directions
- Lines due to uniaxial strain release

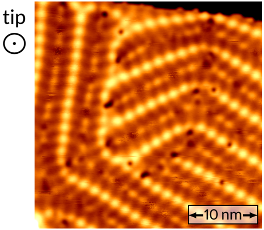
P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

The double layer Fe on Ir(111)



200 mV, 1 nA, 5 K, 0 T





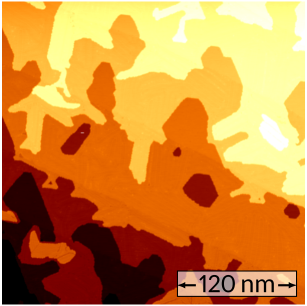
200 mV, 1 nA, 5 K, 4 T

- Reconstruction lines along the 3 equivalent crystallographic directions
- Lines due to uniaxial strain release
- Spin spirals propagate along the lines
- No change in out-of-plane magnetic field up to 9 T

P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116 (2016), 017201.

Incorporate H in the Fe double layer

Constant current map

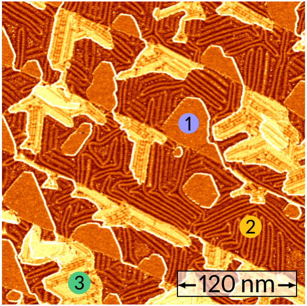


1 V, 1 nA, 4 K, Cr bulk tip

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Incorporate H in the Fe double layer

Differential conductance

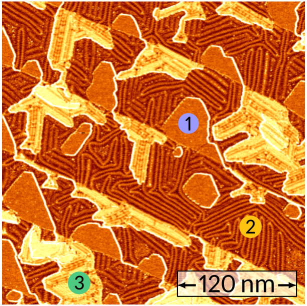


1 V, 1 nA, 4 K, Cr bulk tip

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Incorporate H in the Fe double layer

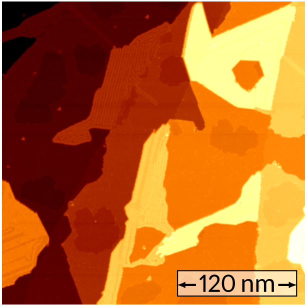
Differential conductance



1 V, 1 nA, 4 K, Cr bulk tip

- H dosing at room temperature
- Post-annealing at 300 °C

Constant current map

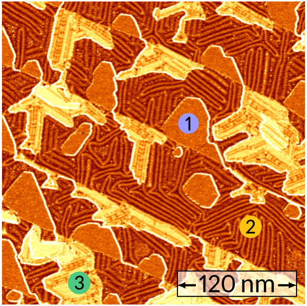


1 V, 1 nA, 4 K, Cr bulk tip

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Incorporate H in the Fe double layer

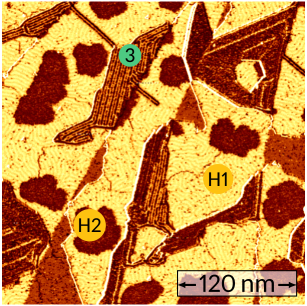
Differential conductance



1 V, 1 nA, 4 K, Cr bulk tip

- H dosing at room temperature
- Post-annealing at 300 °C

Differential conductance

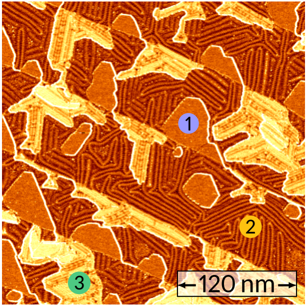


1 V, 1 nA, 4 K, Cr bulk tip

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Incorporate H in the Fe double layer

Differential conductance

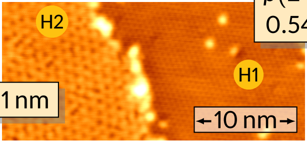


1 V, 1 nA, 4 K, Cr bulk tip

- H dosing at room temperature
- Post-annealing at 300 °C

Constant current map

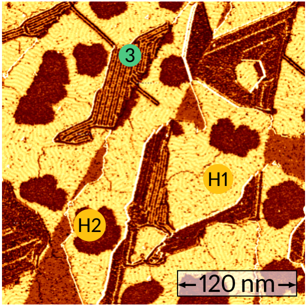
$p(2 \times 2)$
0.54 nm



$\sim$ 1 nm

−200 mV, 1 nA, 4 K, Cr bulk tip

Differential conductance



1 V, 1 nA, 4 K, Cr bulk tip

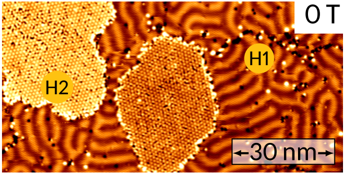
P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Magnetism of the hydrogenated phases

Constant current maps

tip

⊙



−700 mV, 1 nA, 4 K, Cr bulk tip

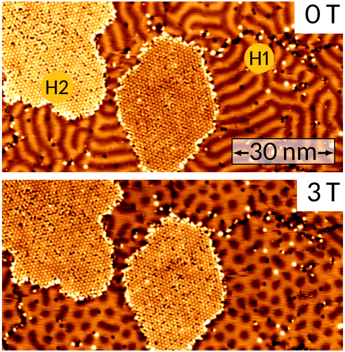
- H1: spin spirals, period 3.5 nm
- H2: ferromagnetic

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Magnetism of the hydrogenated phases

Constant current maps

tip ⊙



−700 mV, 1 nA, 4 K, Cr bulk tip

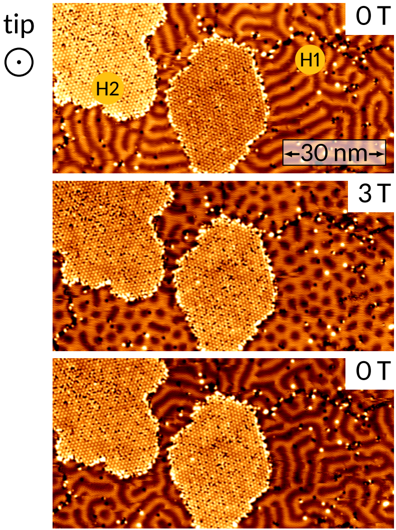
- H1: spin spirals, period 3.5 nm
- H2: ferromagnetic

- H1: creation of skyrmions
- H2: switching

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

Magnetism of the hydrogenated phases

Constant current maps



−700 mV, 1 nA, 4 K, Cr bulk tip

- H1: spin spirals, period 3.5 nm
- H2: ferromagnetic

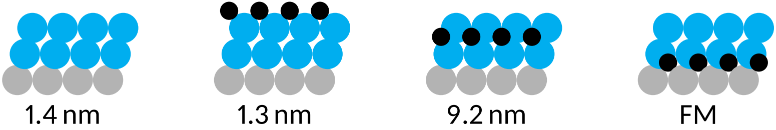
- H1: creation of skyrmions
- H2: switching

P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

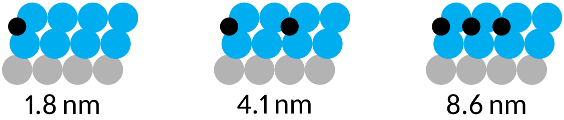
ab initio calculations

done by Levente Rózsa in collaboration with Krisztián Palotás, László Udvardi and László Szunyogh from Budapest

Position of the H atoms



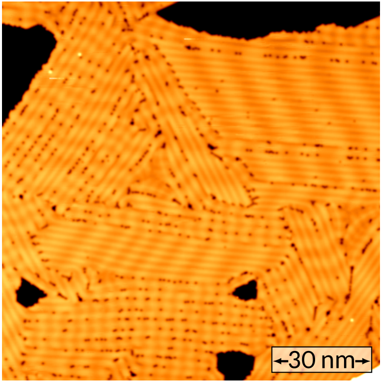
H concentration



P.-J. Hsu *et al.* Inducing skyrmions in ultrathin Fe films by hydrogen exposure. *Nature Communications* 9 (2018), 1571.

The triple layer Fe on Ir(111)

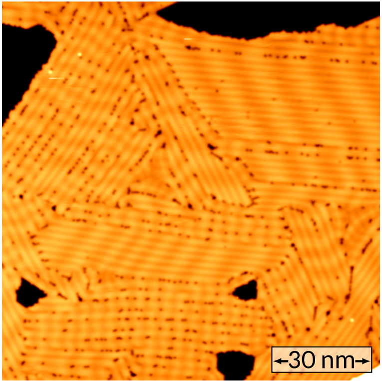
Constant current map



−700 mV, 1 nA, 8 K, 0 T, Cr bulk tip

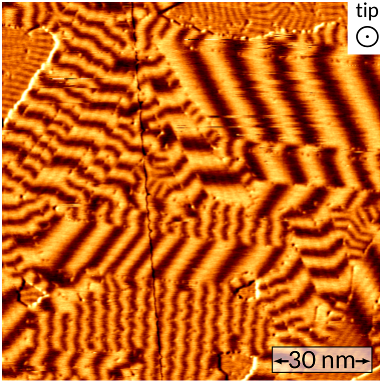
The triple layer Fe on Ir(111)

Constant current map



−700 mV, 1 nA, 8 K, 0 T, Cr bulk tip

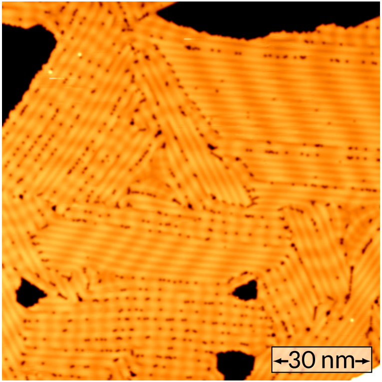
Differential conductance map



- Why do all the spirals look so different?
- What about the temperature stability?

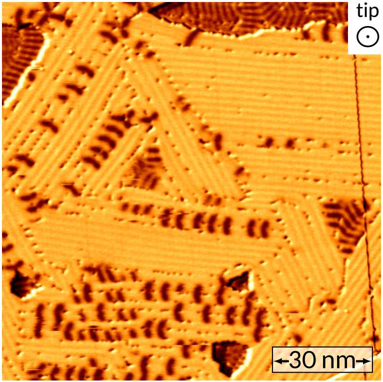
The triple layer Fe on Ir(111)

Constant current map



−700 mV, 1 nA, 8 K, 0 T, Cr bulk tip

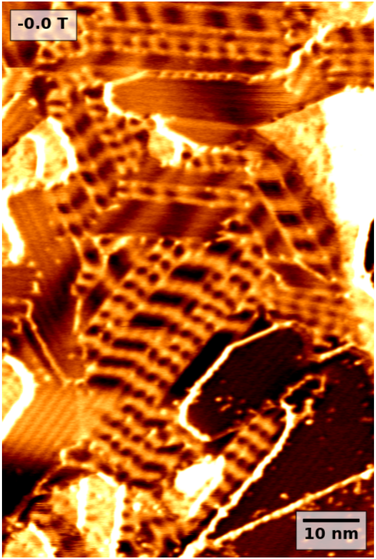
Differential conductance map



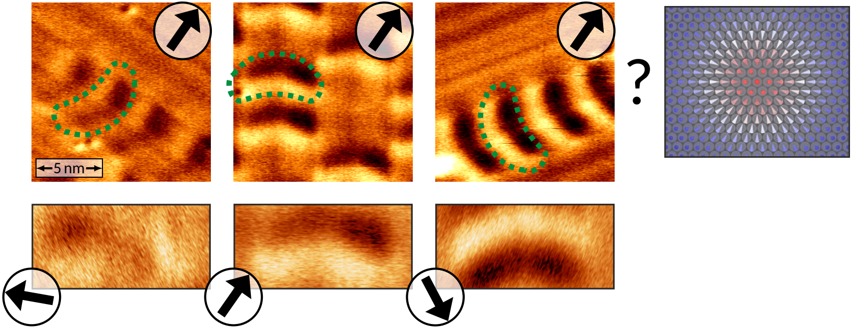
2.5 T

- Why do all the spirals look so different?
- What about the temperature stability?
- How does the magnetic field affect the state? Can we manipulate the created objects?

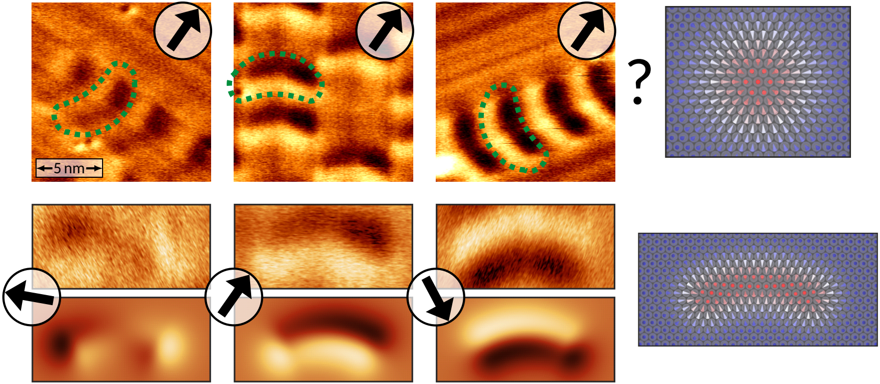
Field dependence of the spirals in the Fe triple layer



Banana shaped skyrmions



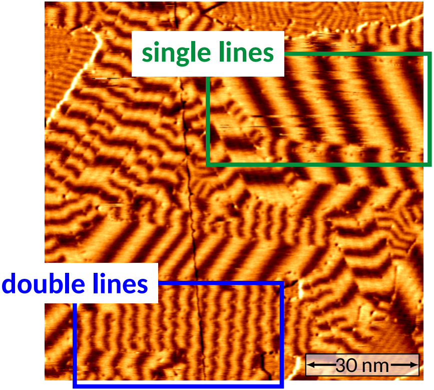
Banana shaped skyrmions



- In-plane sensitive measurements allow to determine the full 3D spin structure
- Same topology as the round skyrmions, but distorted by the surface structure

Coexistence of double and single lines

Differential conductance map

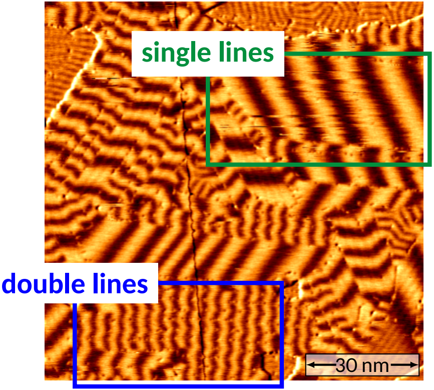


−700 mV, 1 nA, Cr bulk tip, 8 K, 0 T

A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

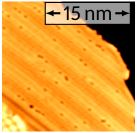
Coexistence of double and single lines

Differential conductance map



−700 mV, 1 nA, Cr bulk tip, 8 K, 0 T

- Double line feature only at positive bias
- Line spacing: 2.2 to 2.8 nm
- Spin spiral period: 3 to 4 nm
- Zigzag spiral wavefront

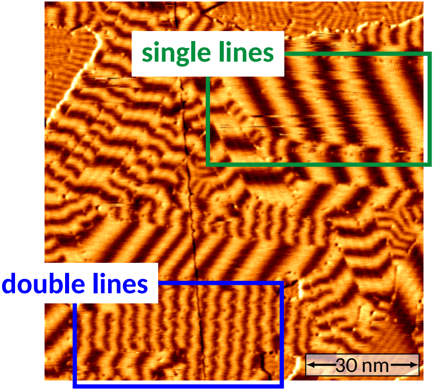


+200 mV

A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

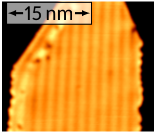
Coexistence of double and single lines

Differential conductance map



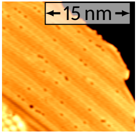
−700 mV, 1 nA, Cr bulk tip, 8 K, 0 T

- Same appearance at any bias, positive or negative
- Line spacing: 1.8 to 2.2 nm
- Spin spiral period: 5 to 10 nm
- Straight but canted spiral wavefront



+200 mV

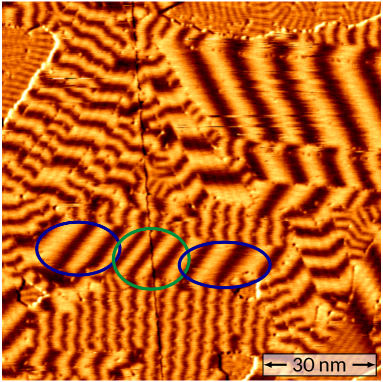
- Double line feature only at positive bias
- Line spacing: 2.2 to 2.8 nm
- Spin spiral period: 3 to 4 nm
- Zigzag spiral wavefront



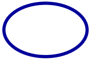
+200 mV

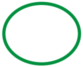
A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Varying spin spiral period



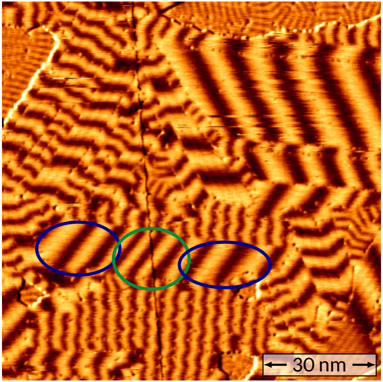
Dislocation lines spacing:


1.85 nm


2.1 nm

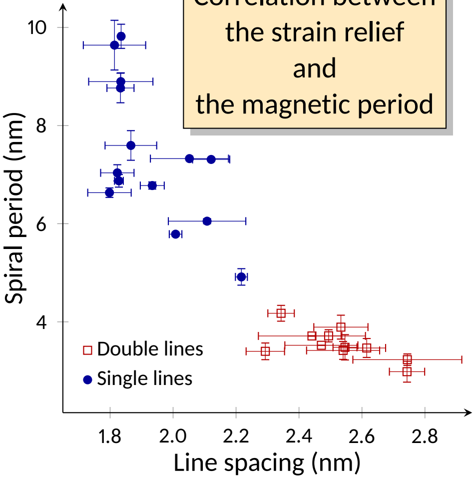
A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Varying spin spiral period



Dislocation lines spacing:

1.85 nm 2.1 nm

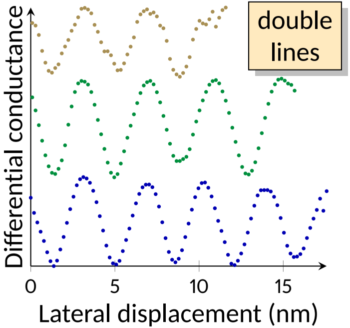


Correlation between the strain relief and the magnetic period

A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

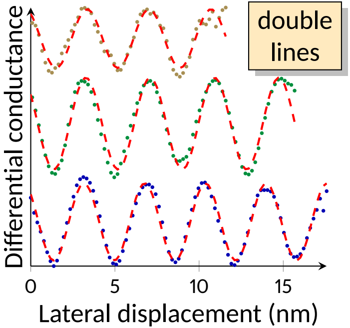
Effective magnetic anisotropy

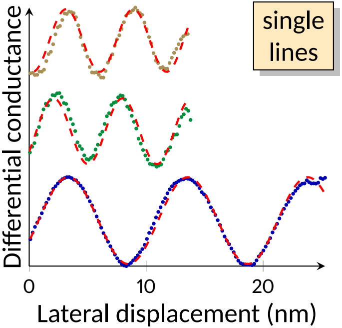
- Line profiles from several spirals with various periods



Effective magnetic anisotropy

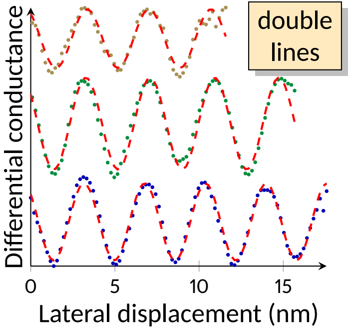
- Line profiles from several spirals with various periods
- Fitting a sine function

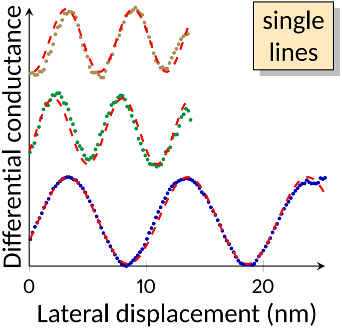




Effective magnetic anisotropy

- Line profiles from several spirals with various periods
- Fitting a sine function





- Homogeneous spin spirals $\Longrightarrow$ very small anisotropy!

Simple magnetic model

1D model: $$E = A \sum_i \left(\frac{\partial \mathbf{m}}{\partial x_i}\right)^2 + D\left(\mathrm{m}_z \frac{\partial \mathrm{m}_x}{\partial x} - \mathrm{m}_x \frac{\partial \mathrm{m}_z}{\partial x}\right) - K_{\mathrm{eff}} \mathrm{m}_z^2$$

- We assume that D is not affected by the strain variations
- We take $K_{\mathrm{eff}} = 0$

$\Longrightarrow$ Spin spiral period: $$\lambda = 4\pi \frac{A}{|D|}$$

$D = 2.8\,\mathrm{mJ\,m^{-2}}$
(Fe/Ir interface)

$3\,\mathrm{nm} \leqslant \lambda \leqslant 10\,\mathrm{nm}$

$\updownarrow$

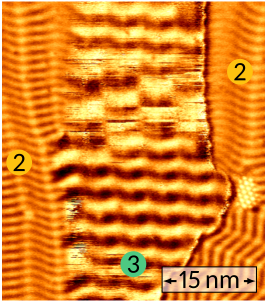
$0.6\,\mathrm{pJ\,m^{-1}} \leqslant A \leqslant 2.2\,\mathrm{pJ\,m^{-1}}$

A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *Journal of Magnetism and Magnetic Mat.* 138.3 (1994), 255–269.

Improved thermal stability

- The nanoskyrmion lattice in the monolayer disappears at 28 K

43 K



−700 mV, 1 nA

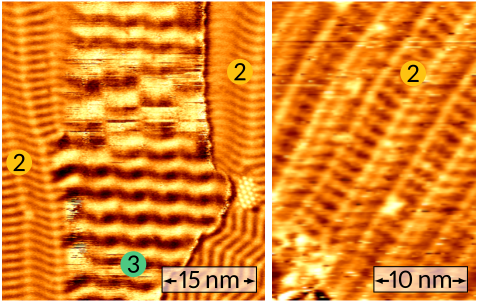
A. Sonntag *et al.* Thermal Stability of an Interface-Stabilized Skyrmion Lattice. *Phys. Rev. Lett.* 113 (2014).

A. Finco *et al.* Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

Improved thermal stability

- The nanoskyrmion lattice in the monolayer disappears at 28 K

43 K **153 K**



−700 mV, 1 nA −500 mV, 2 nA

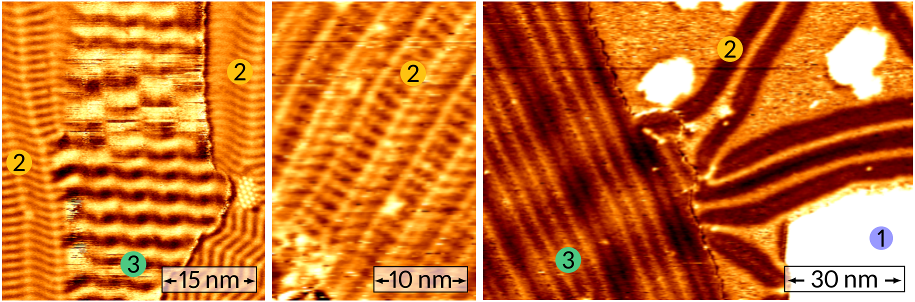
A. Sonntag *et al*. Thermal Stability of an Interface-Stabilized Skyrmion Lattice. *Phys. Rev. Lett*. 113 (2014).

A. Finco *et al*. Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

Improved thermal stability

- The nanoskyrmion lattice in the monolayer disappears at 28 K
- The spin spirals in the double layer disappear below 200 K

43 K **153 K** **200 K**



−700 mV, 1 nA

−500 mV, 2 nA

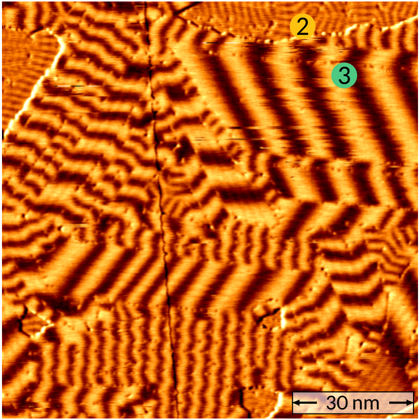
−700 mV, 2 nA, 0 T, Fe coated W tip

A. Sonntag *et al.* Thermal Stability of an Interface-Stabilized Skyrmion Lattice. *Phys. Rev. Lett.* 113 (2014).

A. Finco *et al.* Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

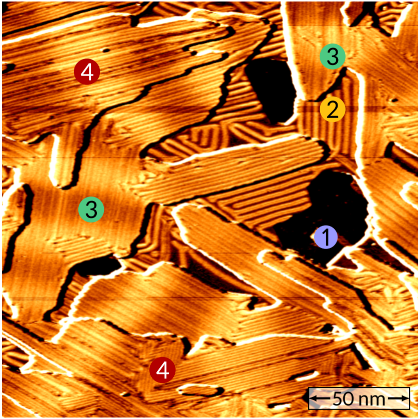
Room temperature spin spirals in the triple layer

8 K



−700 mV, 1 nA, 0 T, Cr bulk tip

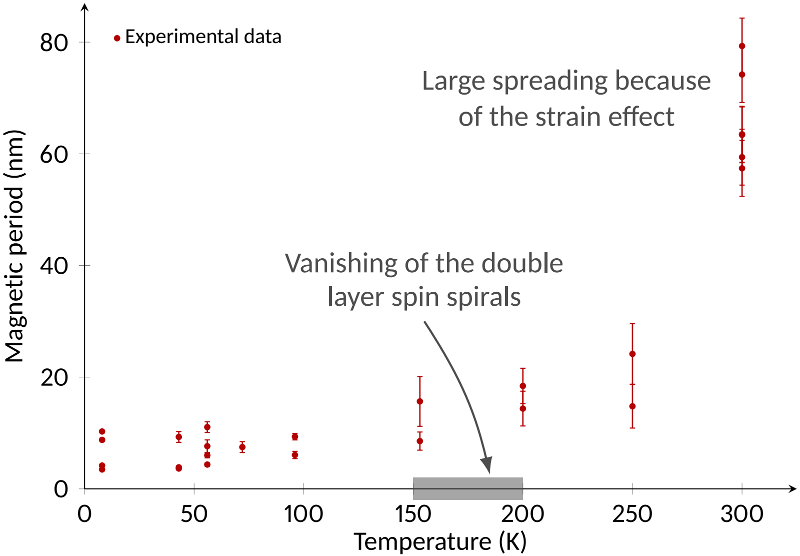
300 K



−500 mV, 3 nA, 0 T, Cr bulk tip

A. Finco *et al*. Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

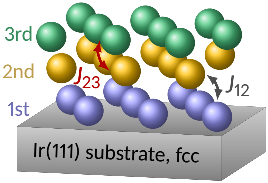
Increased spin spiral period



A. Finco *et al.* Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

Classical model: different layers

proposed by Levente Rózsa



- We assume again $K_{eff} = 0$
- Different parameters in the 3 layers
- Interlayer exchange couplings

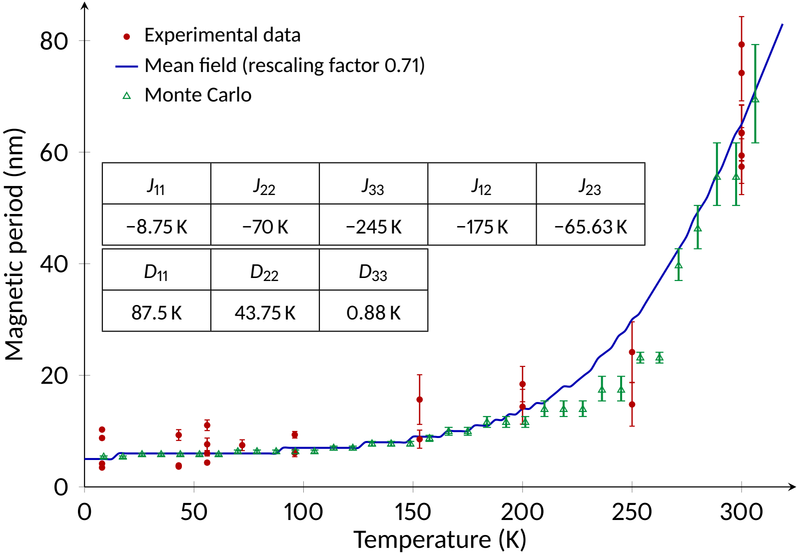
Hamiltonian:

$$H = \frac{1}{2} \sum_{p,q,\langle i,j \rangle} J_{pq,ij}\, \mathbf{S}_{p,i}\, \mathbf{S}_{q,j} + \frac{1}{2} \sum_{p,\langle i,j \rangle} \mathbf{D}_{pp,ij} \left(\mathbf{S}_{p,i} \times \mathbf{S}_{p,j} \right)$$

- The mean field order parameter $\langle S_p(k) \rangle$ **decreases faster with temperature** in the 1st and 2nd layers than in the 3rd one.
- This **shifts the free energy minimum towards larger periods**
- Parameters chosen to reproduce the data

A. Finco *et al.* Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

Comparison to the experiment

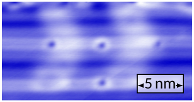


J_{11}	J_{22}	J_{33}	J_{12}	J_{23}
−8.75 K	−70 K	−245 K	−175 K	−65.63 K

D_{11}	D_{22}	D_{33}
87.5 K	43.75 K	0.88 K

A. Finco *et al.* Temperature-Induced Increase of Spin Spiral Periods. *Physical Review Letters* 119.3 (2017), 037202.

Skyrmion switching with non-magnetic tips!

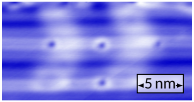


200 mV, 1 nA, 8 K, −1.85 T, W tip

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

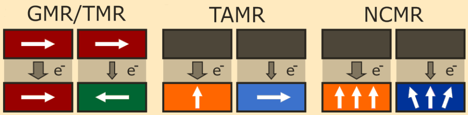
Skyrmion switching with non-magnetic tips!



200 mV, 1 nA, 8 K, −1.85 T, W tip

Imaging mechanism:

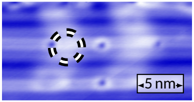
Non-Collinear MagnetoResistance



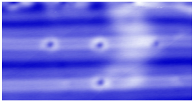
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

Skyrmion switching with non-magnetic tips!

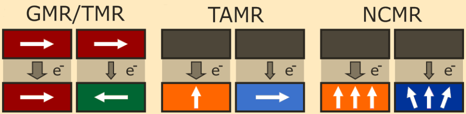


200 mV, 1 nA, 8 K, −1.85 T, W tip



Imaging mechanism:

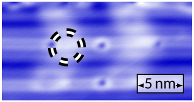
Non-Collinear MagnetoResistance



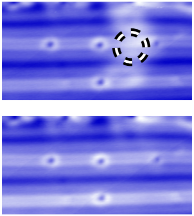
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

Skyrmion switching with non-magnetic tips!

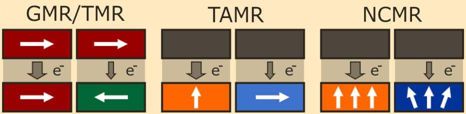


200 mV, 1 nA, 8 K, −1.85 T, W tip



Imaging mechanism:

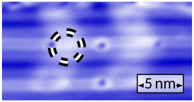
Non-Collinear MagnetoResistance



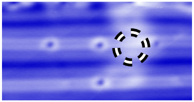
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

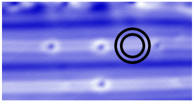
C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

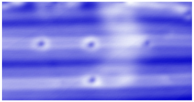
Skyrmion switching with non-magnetic tips!



200 mV, 1 nA, 8 K, −1.85 T, W tip

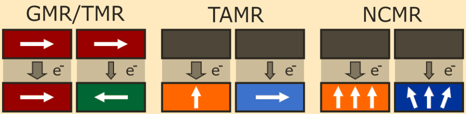






Imaging mechanism:

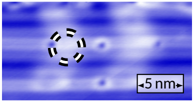
Non-Collinear MagnetoResistance



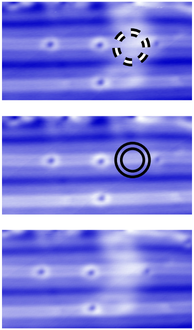
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

Skyrmion switching with non-magnetic tips!

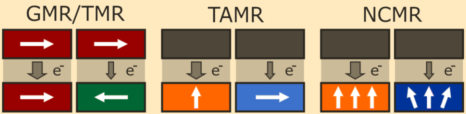


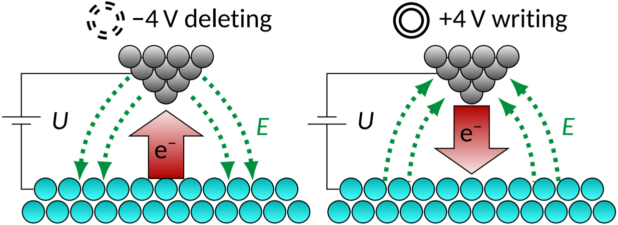
200 mV, 1 nA, 8 K, −1.85 T, W tip



Imaging mechanism:

Non-Collinear MagnetoResistance





P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

Electric field driven switching

- Spin-polarized tip **not** needed
- Opposite polarity for writing and deleting

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Electric field driven switching

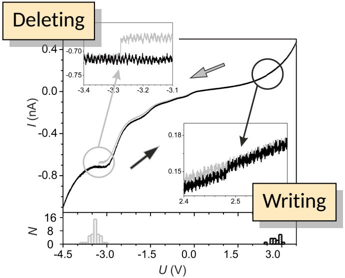
- Spin-polarized tip **not** needed
- Opposite polarity for writing and deleting
- Parallel plates model: $E = -U/d$
  - Measure the switching voltage *U* for different tip/sample distances *d*

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Electric field driven switching

- Spin-polarized tip **not** needed
- Opposite polarity for writing and deleting
- Parallel plates model: $E = {}^{-U}/_{d}$
  - Measure the switching voltage *U* for different tip/sample distances *d*

How do we measure *U*?

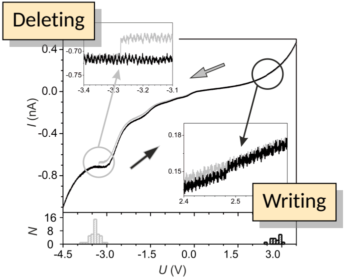


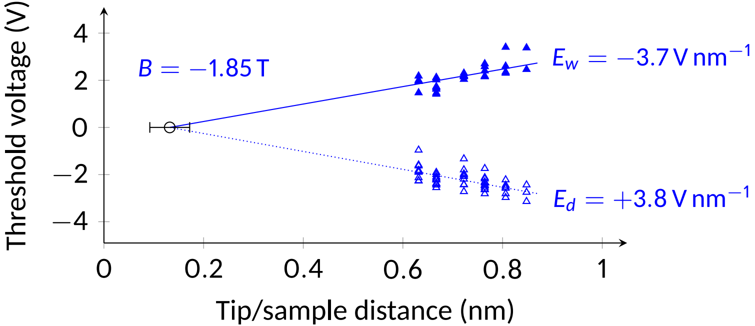
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Electric field driven switching

- Spin-polarized tip **not** needed
- Opposite polarity for writing and deleting
- Parallel plates model: $E = -U/d$
  - Measure the switching voltage *U* for different tip/sample distances *d*

How do we measure *U*?



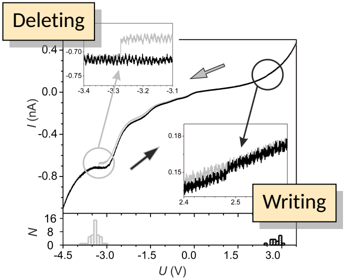


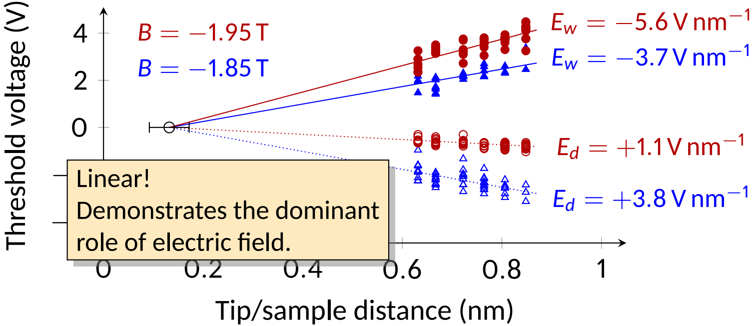
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Electric field driven switching

- Spin-polarized tip **not** needed
- Opposite polarity for writing and deleting
- Parallel plates model: $E = -U/d$
  - Measure the switching voltage *U* for different tip/sample distances *d*

How do we measure *U*?



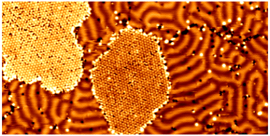


Linear!
Demonstrates the dominant role of electric field.

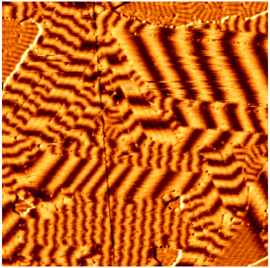
P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Summary

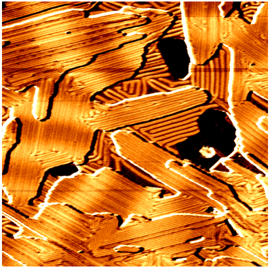
H incorporation



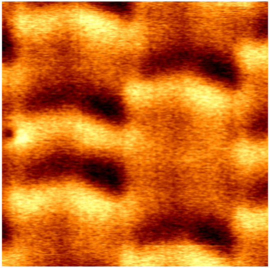
Epitaxial strain



Temperature



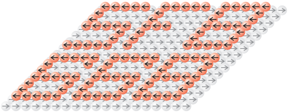
Electric field



Acknowledgements

Pin-Jui Hsu
Niklas Romming
Lorenz Schmidt
Thomas Eelbo
André Kubetzka
Kirsten von Bergmann
Levente Rózsa
Elena Vedmedenko
Roland Wiesendanger
Krisztián Palotás
László Udvardi
László Szunyogh

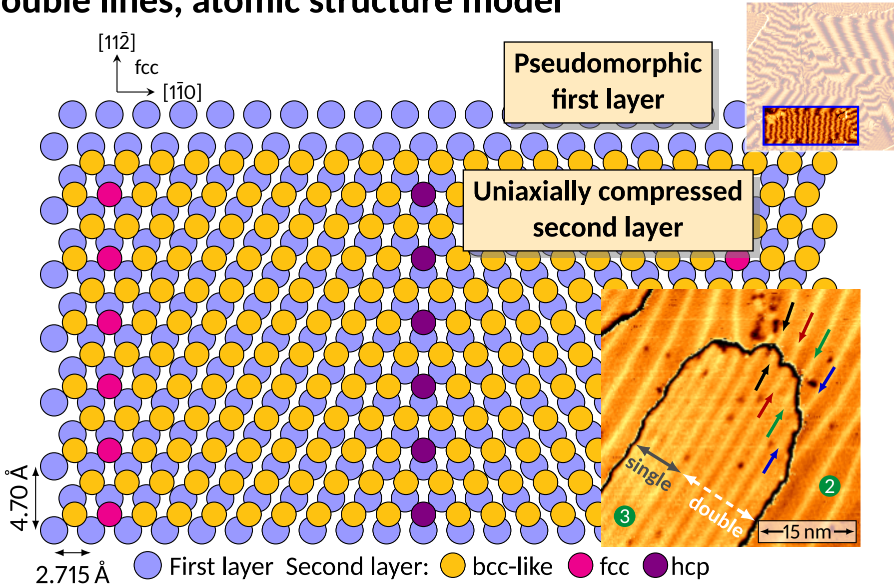
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



MAGicSky

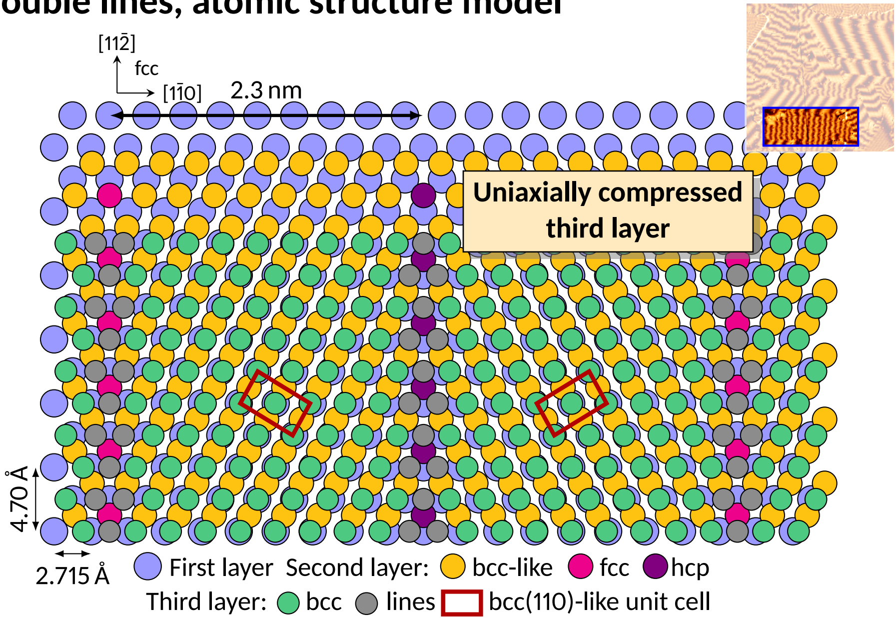
Funded by the Horizon2020 Framework Programme of the European Union

Double lines, atomic structure model



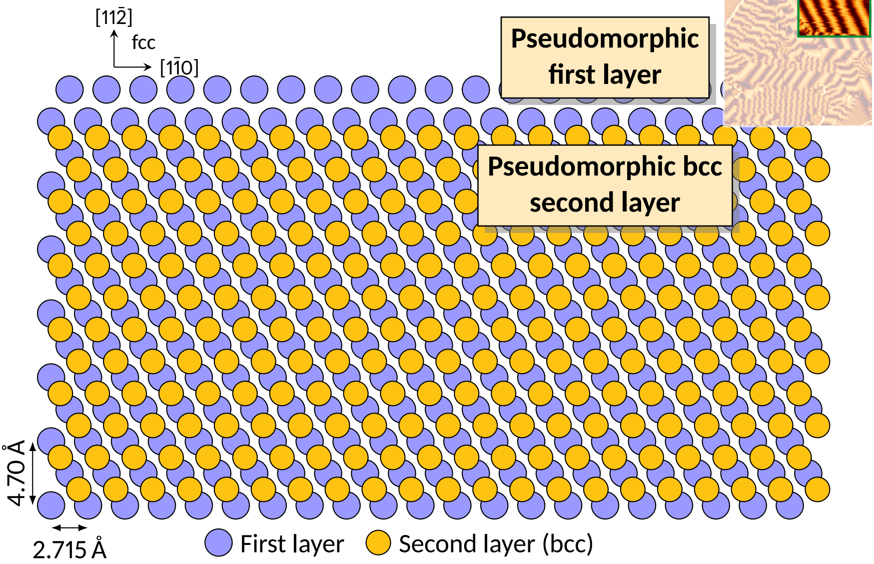
A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Double lines, atomic structure model



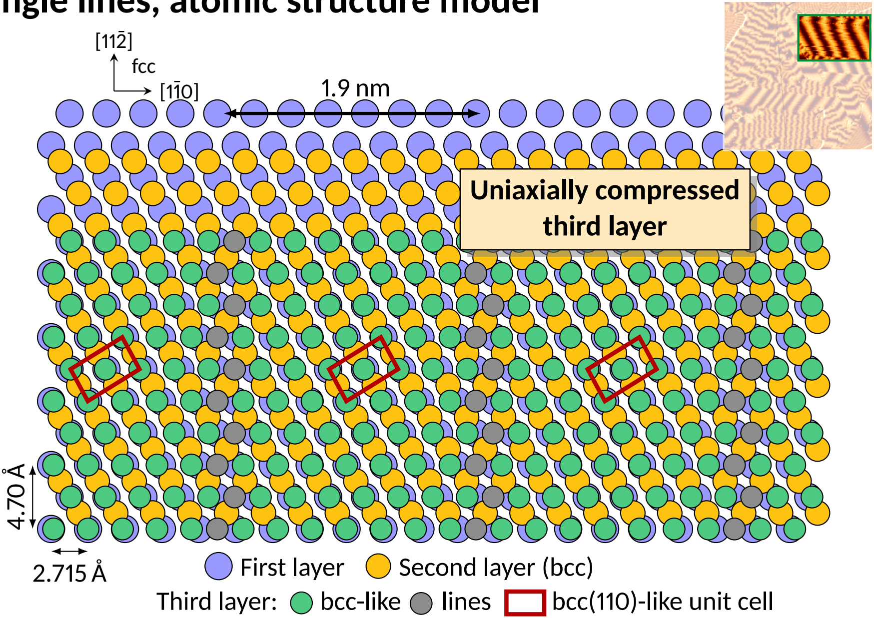
A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Single lines, atomic structure model



A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

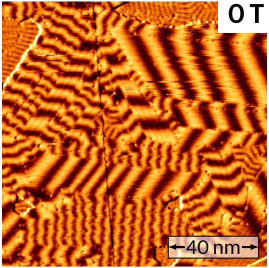
Single lines, atomic structure model

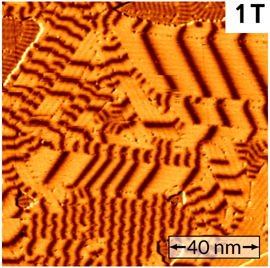


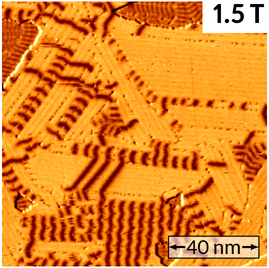
A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Magnetic phase transition

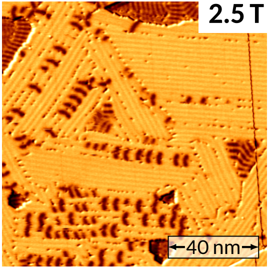
Differential conductance maps, out-of-plane sensitive tip





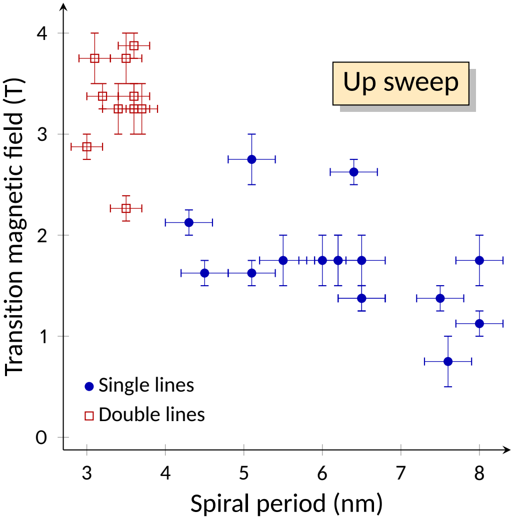


−700 mV, 1 nA, 8 K, Cr bulk tip



- Spirals in single lines areas become **360° domain walls**
- Spirals in double lines areas become **skyrmions**
- Different transition field in every area
  - Variation of the strain relief
  - Pinning on defects
  - Interaction between the adjacent areas

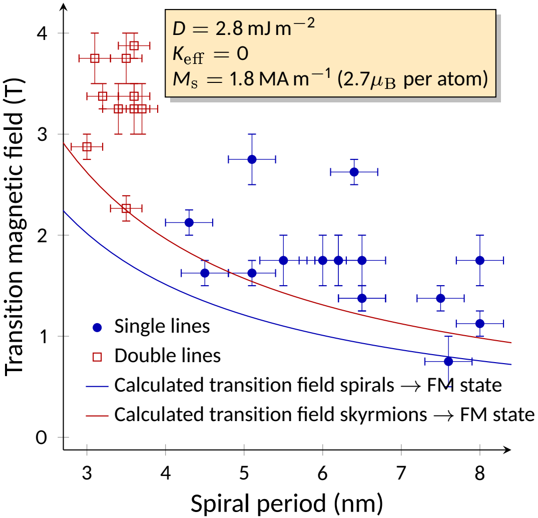
Effect of the dislocation line spacing on the transition field



A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *Journal of Magnetism and Magnetic Mat.* 138.3 (1994), 255–269.

A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Effect of the dislocation line spacing on the transition field



Back to the model, with a Zeeman term:

$$\mathcal{E} = A\sum_i \left(\frac{\partial \mathbf{m}}{\partial x_i}\right)^2 + D\left(\mathrm{m}_z\frac{\partial \mathrm{m}_x}{\partial x} - \mathrm{m}_x\frac{\partial \mathrm{m}_z}{\partial x}\right) - K_{\mathrm{eff}} m_z^2 - M_{\mathrm{s}} B m_z$$

$$\mathrm{B_t} = \frac{D^2 h_{\mathrm{t}}}{A M_{\mathrm{s}}} = 4\pi\frac{D h_{\mathrm{t}}}{\lambda M_{\mathrm{s}}}$$

$$h_{\mathrm{t}}^{\mathrm{spiral}}(K_{\mathrm{eff}} = 0) = 0.308$$

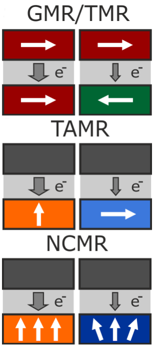
$$h_{\mathrm{t}}^{\mathrm{skyrmion}}(K_{\mathrm{eff}} = 0) = 0.401$$

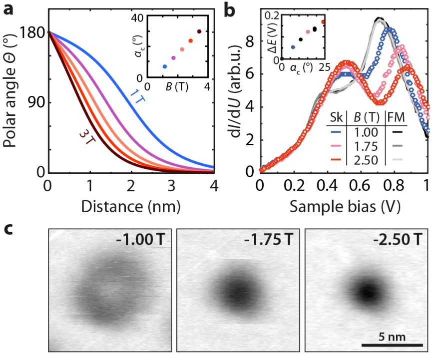
A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *Journal of Magnetism and Magnetic Mat.* 138.3 (1994), 255–269.

A. Finco *et al.* Tailoring noncollinear magnetism by misfit dislocation lines. *Physical Review B* 94.21 (2016), 214402.

Noncollinear magnetoresistance (NCMR)

- Observed first for the skyrmions in PdFe/Ir(111)
- Non collinearity of the spin texture ⇒ different local electronic structure than the FM background
- Scales with the angle between nearest neighbors magnetic moments





C. Hanneken *et al.* Electrical detection of magnetic skyrmions by tunnelling non-collinear magnetoresistance. *Nature Nano.* 10 (2015), 1039–1042.

Manipulating the skyrmions

- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps

Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Manipulating the skyrmions

- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps

Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Manipulating the skyrmions

- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps

Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Manipulating the skyrmions

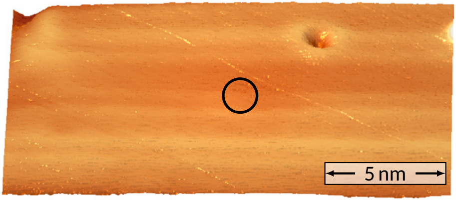
- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps

Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Manipulating the skyrmions

- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps



Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Manipulating the skyrmions

- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps

Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Manipulating the skyrmions

- Reliable skyrmion switching with a Cr bulk tip
- Writing with +3 V ramps
- Deleting with −3 V ramps

Imaging: 300 mV, 0.5 nA, 8 K, 2.5 T

P.-J. Hsu *et al.* Electric-field-driven switching of individual magnetic skyrmions. *Nature Nano* 12 (2017), 123–126.

Switching with a Cr bulk tip