Universität Hamburg

Electric field switching of skyrmions and non-collinear magnetism at room temperature investigated by STM techniques

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André Kubetzka, Kirsten von Bergmann
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University of Hamburg, Germany

Magnetic structures

Collinear structures

Magnetic structures

Collinear structures

Ferromagnets,

Fe, *Co*

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Ferromagnets, Antiferromagnets,

Fe, Co

Cr, NiO

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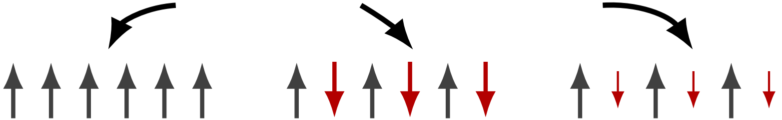

Fe, Co *Cr, NiO* *Fe_3O_4*

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Exchange interaction: $\mathcal{E}_{\mathbf{ex}} = \mathbf{J_{ij}\, S_i \cdot S_j}$

Anisotropy

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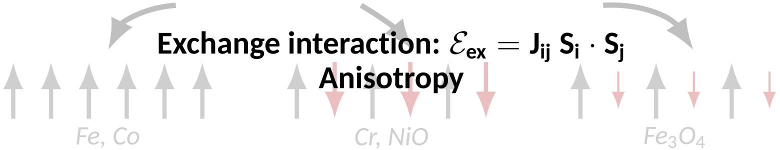

Non-collinear structures

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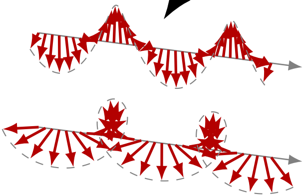
Spin spirals,



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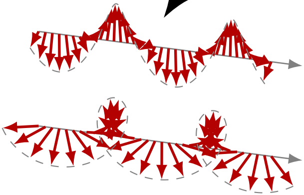
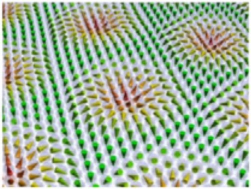
Spin spirals, Skyrmions





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Exchange interaction: $\mathcal{E}_{\mathbf{ex}} = \mathbf{J_{ij}}\, \mathbf{S_i} \cdot \mathbf{S_j}$

Anisotropy

Non-collinear structures

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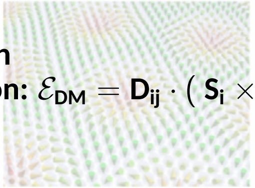
Frustration

Dzyaloshinskii-Moriya interaction: $\mathcal{E}_{\mathbf{DM}} = \mathbf{D_{ij}} \cdot (\, \mathbf{S_i} \times \mathbf{S_j})$

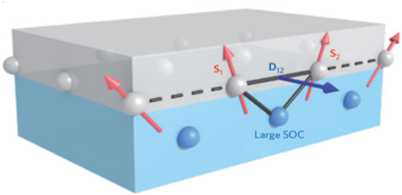


The Dzyaloshinskii-Moriya interaction

DMI: **antisymmetric** interaction between 2 spins, effect of spin-orbit coupling on the exchange, $\mathcal{E}_{DM} = D_{ij} \cdot (S_i \times S_j)$

exists only if there is **no inversion symmetry** in the system

- *Multiferroics*: ionic displacements $\Rightarrow$ symmetry breaking and electric polarization
- *B20 compounds*: skyrmion lattice phase (bulk) ex: MnSi, Cu_2OSeO_3
- *Ultrathin films*: interface induced DMI



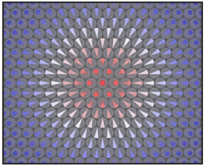
T. Moriya. Anisotropic superexchange interaction and weak ferromagnetism. *Physical Review* 120.1 (1960).

I. Dzyaloshinskii. A thermodynamic theory of “weak” ferromagnetism of antiferromagnetics. *Journal of Physics and Chemistry of Solids* 4.4 (1958).

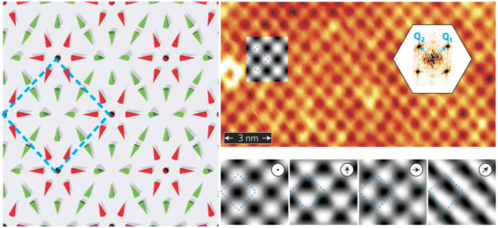
A. Fert *et al*. Skyrmions on the track. *Nature nanotechnology* 8.3 (2013).

Skyrmions in ultrathin films

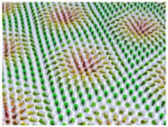
- Skyrmions: topologically protected particle-like magnetic structures, solitons
- Stabilized in ultrathin films by the DMI $\Rightarrow$ fixed rotational sense

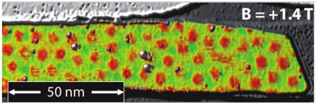


Monolayer Fe on Ir(111)



Pd/Fe bilayer on Ir(111)



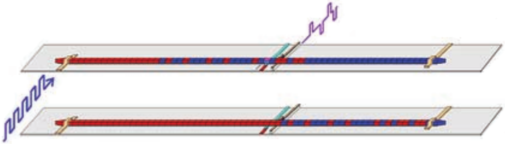


A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *Journal of magnetism and magnetic materials* 138.3 (1994).

Stefan Heinze *et al.* Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nature Physics* 7.9 (2011).

N. Romming *et al.* Writing and deleting single magnetic skyrmions. *Science* 341.6146 (2013).

Skyrmion-based racetrack memories



Racetrack memory with domain walls

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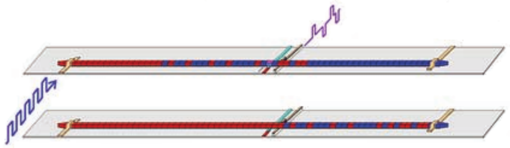

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- Skyrmions can be small (4 nm in Pd/Fe/Ir(111)).
- They can be written and deleted.
- They can be moved by lateral currents (up to $100\,\mathrm{m\,s^{-1}}$ in CoFeB multilayers).

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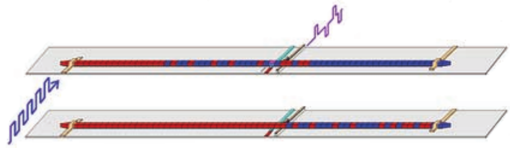

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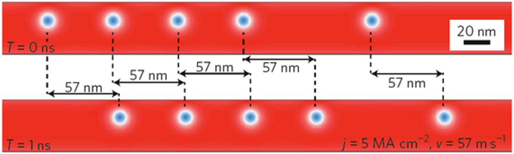

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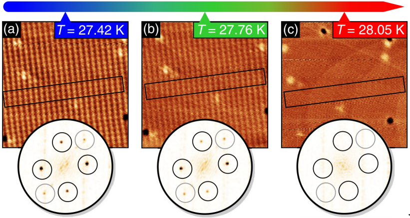
Why 3 Fe layers on Ir(111)?



Nanoskymion lattice visible until 28 K

We need to improve the thermal stability!

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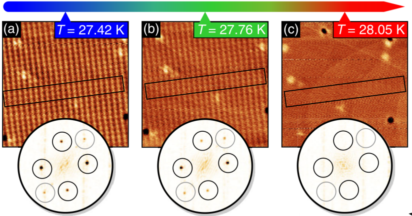

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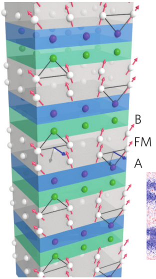
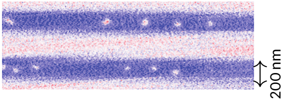


Multilayer stacks

Example:

$(Ir/Co/Pt)_x$



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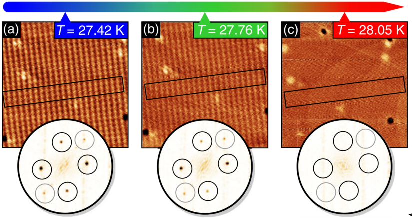

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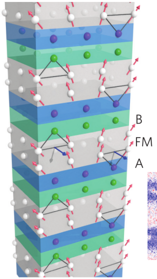

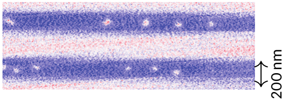

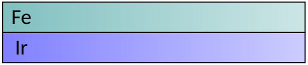

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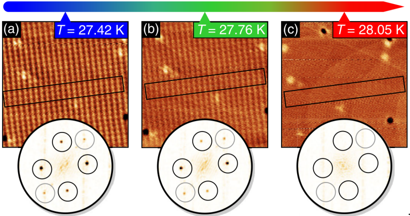

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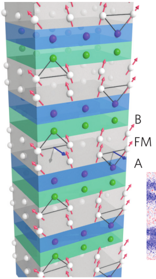

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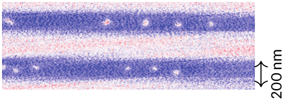
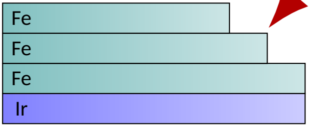


Go to higher coverage



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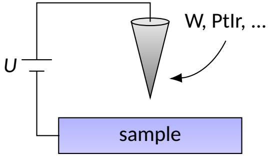
Spin-polarized scanning tunneling microscopy

STM setup

- UHV for sample preparation and measurements
- Low temperature (8 or 4 K) STM with magnetic field up to 2.5 or 9 T
- Vector field STM (5 K), magnetic field in any direction
- Variable temperature, no magnetic field



$$I_0 = \frac{U}{R_{QPC}} e^{-2\kappa d}$$

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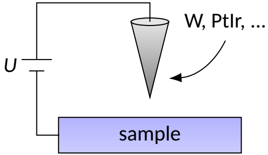

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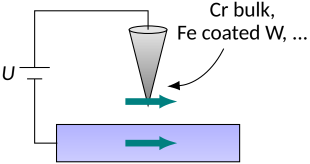
SP-STM



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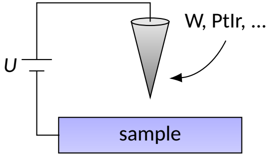

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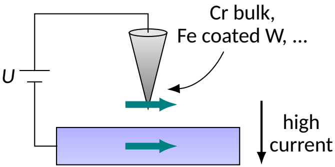

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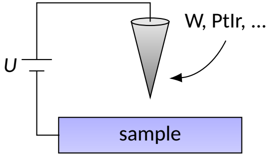

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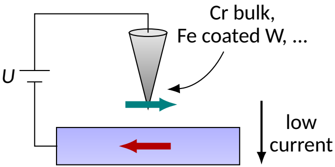

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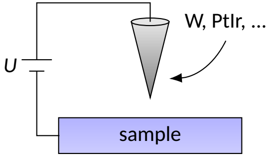

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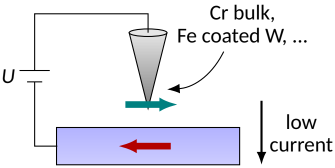

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Versatile technique

Measurement of the 3D magnetic structure down to the atomic scale

Manipulation of the magnetic state

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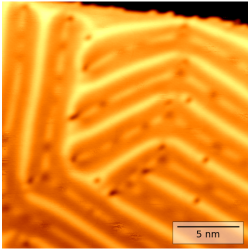
The double layer Fe on Ir(111)



$U = 200\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 5\,\mathrm{K}$, $B = 0\,\mathrm{T}$

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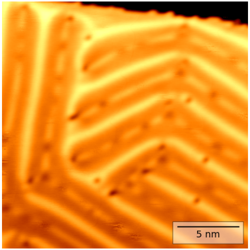

$U = 200\,\text{mV}$, $I = 1\,\text{nA}$, $T = 5\,\text{K}$, $B = 0\,\text{T}$

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

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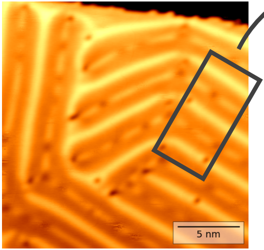

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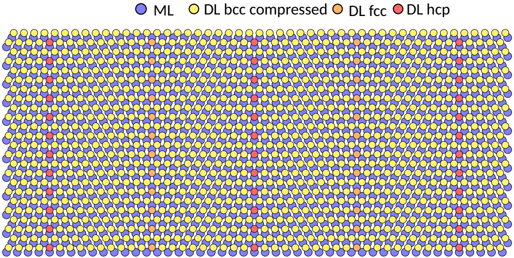
Structure model



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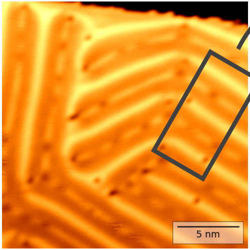

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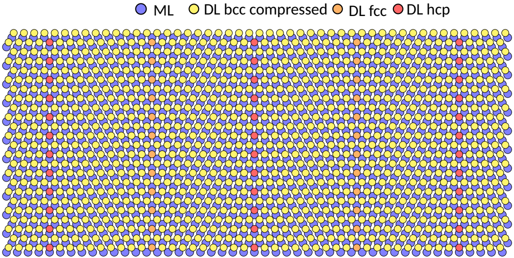

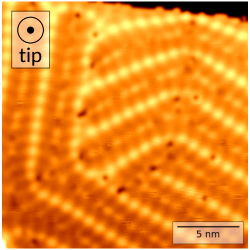

$U = 200\,\text{mV}$, $I = 1\,\text{nA}$, $T = 5\,\text{K}$, $B = 4\,\text{T}$

- 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
- Observed up to 150 K

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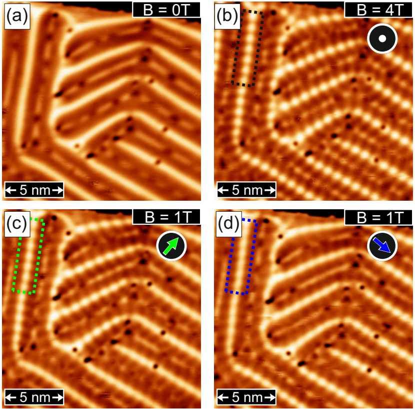
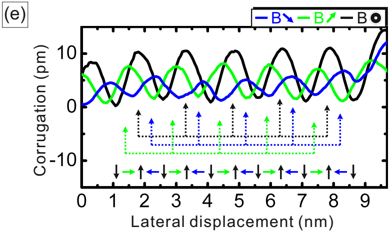
Cycloidal spirals on the double layer



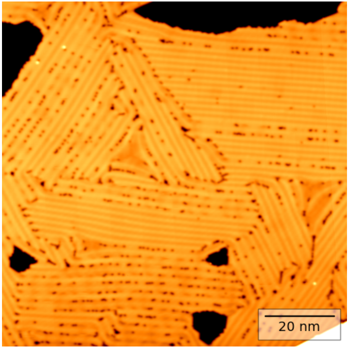
- W tip with a Fe cluster at the end
- Superparamagnetic:
  - spin averaging when $B = 0\,\mathrm{T}$
  - aligned with the external magnetic field
- Measurement in the vector field system
- **The spin spirals are cycloidal!**



P-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Phys. Rev. Lett.* 116 (2016).

The triple layer Fe on Ir(111)

Topography



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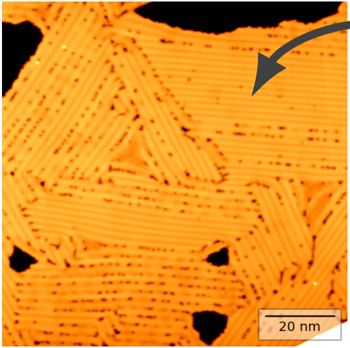
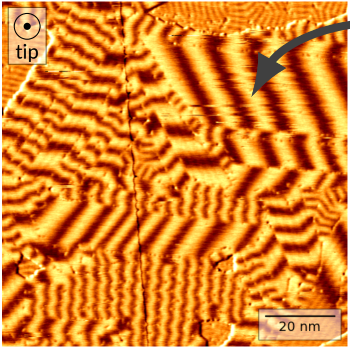


Reconstructed surface due to strain release

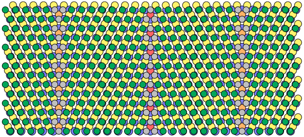
The triple layer Fe on Ir(111)

Differential conductance, B=0 T, T=8 K



Reconstructed surface due to strain release

Determination of the shape of the wavefront and the magnetic periodicity



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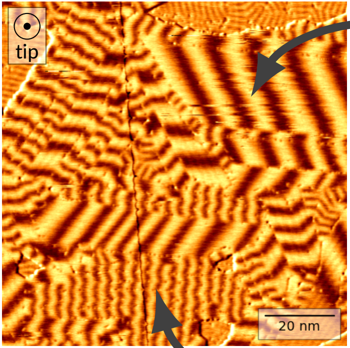

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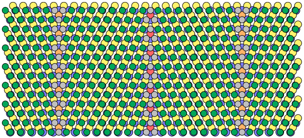
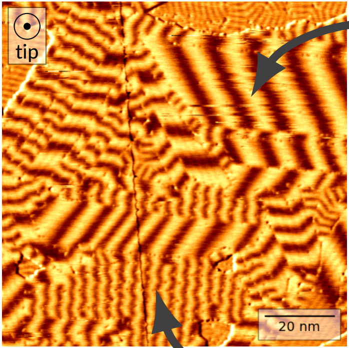


Application of external magnetic fields

The triple layer Fe on Ir(111)

Differential conductance, B=0 T, T=8 K



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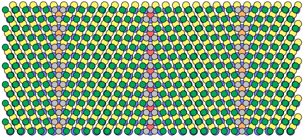
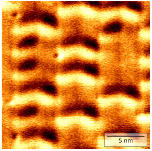


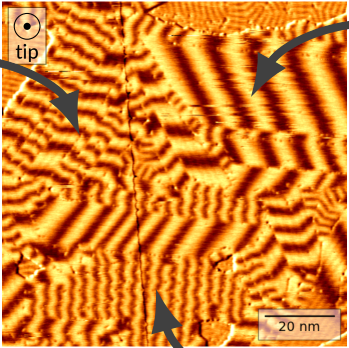
Application of external magnetic fields



Creation of distorted magnetic skyrmions manipulable with electric fields

The triple layer Fe on Ir(111)

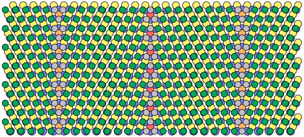
Differential conductance, B=0 T, T=8 K



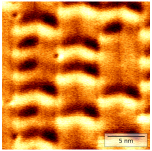
Temperature increase

Reconstructed surface due to strain release

Determination of the shape of the wavefront and the magnetic periodicity



Application of external magnetic fields



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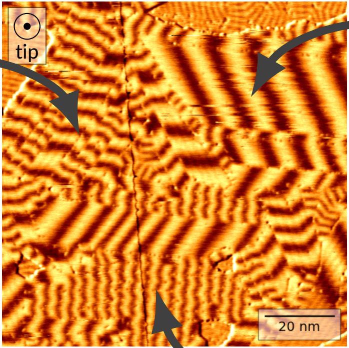
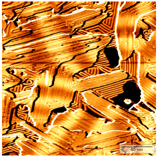


Temperature increase

Magnetic periodicity up to 10 times larger at RT



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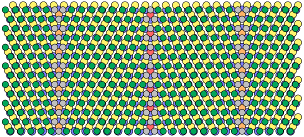
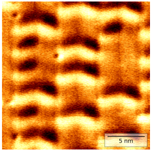


Application of external magnetic fields

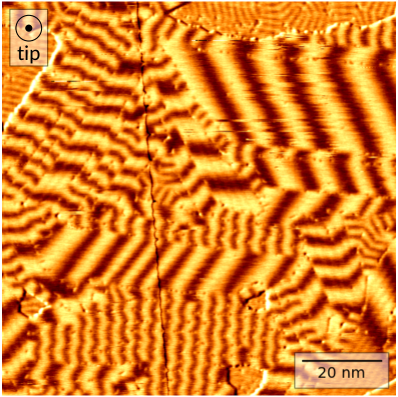


Creation of distorted magnetic skyrmions manipulable with electric fields

Magnetic structure

No external magnetic field

Differential conductance, $B = 0\,\mathrm{T}$, $T = 8\,\mathrm{K}$



$U = -700\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$

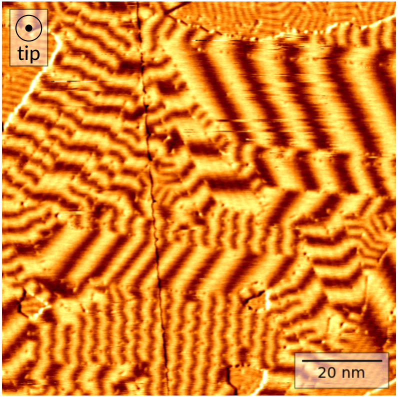
Cycloidal spin spirals guided by the reconstruction lines

K. von Bergmann *et al.* Interface-induced chiral domain walls, spin spirals and skyrmions revealed by spin-polarized scanning tunneling microscopy. *Journal of Physics: Condensed Matter* 26.39 (2014).

Magnetic structure

No external magnetic field

Differential conductance, $B = 0\,\mathrm{T}$, $T = 8\,\mathrm{K}$



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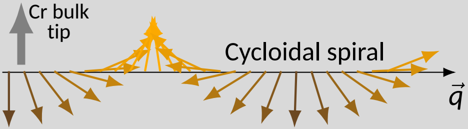


- Rotational sense given by the sign of the DMI
- Periodicity $\propto J/D$

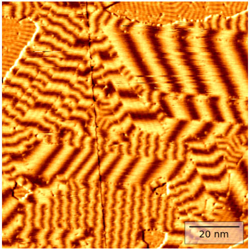
Wavelenght of the spirals between 3.5 and 12 nm

K. von Bergmann *et al.* Interface-induced chiral domain walls, spin spirals and skyrmions revealed by spin-polarized scanning tunneling microscopy. *Journal of Physics: Condensed Matter* 26.39 (2014).

Magnetic structure of the triple layer at elevated temperatures

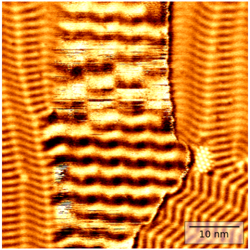
No external magnetic field!

8 K



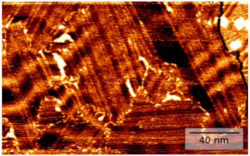
$U = -700\,\text{mV}$, $I = 1\,\text{nA}$
Cr bulk tip

43 K



$U = -700\,\text{mV}$, $I = 0.7\,\text{nA}$
Fe coated W tip

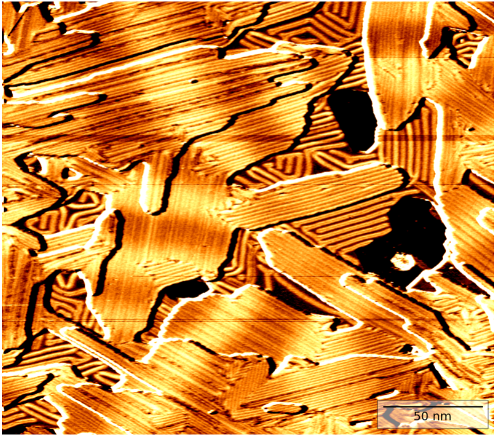
200 K



$U = -700\,\text{mV}$, $I = 2\,\text{nA}$
Fe coated W tip

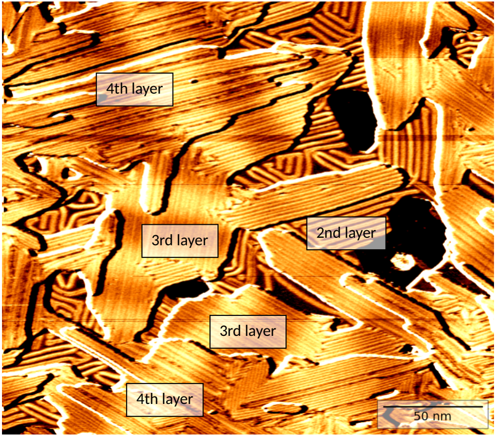
- The spin spirals on the double layer disappear between 150 and 200 K
- On the triple layer, the spirals are still present at 200 K
- Some changes in the shape of the wavefront and in the periodicity are already visible at 200 K

Room temperature spin spirals



$U = -500\,\mathrm{mV}$, $I = 3\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Cr bulk tip

Room temperature spin spirals



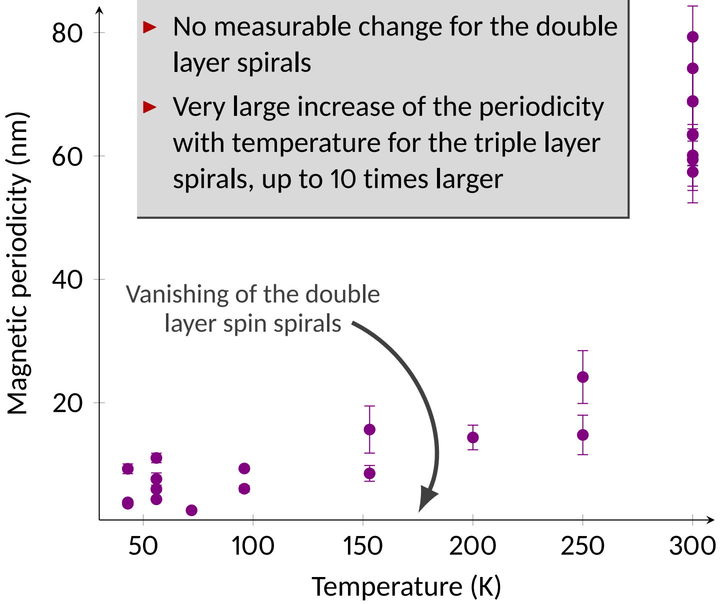
$U = -500\,\text{mV}, I = 3\,\text{nA}, B = 0\,\text{T}$, Cr bulk tip

- Spin spirals visible on the 3rd and 4th layers.
- Direction of the wavevector still given by the reconstruction lines
- Periodicity between 60 and 80 nm
- The spirals are crossing the different layers

- **The local atom arrangement affects only the propagation direction and not the wavefront anymore.**
- **A coupling between the layers seems to become important at room temperature.**

Increase of the magnetic periodicity with temperature

- No measurable change for the double layer spirals
- Very large increase of the periodicity with temperature for the triple layer spirals, up to 10 times larger



Temperature dependence of the triple layer Fe on Ir(111)

Spin spirals are stable on the triple layer Fe on Ir(111) up to room temperature

The wavelength of the spin spirals increases drastically with temperature, from between 3.5 and 12 nm to between 60 and 80 nm

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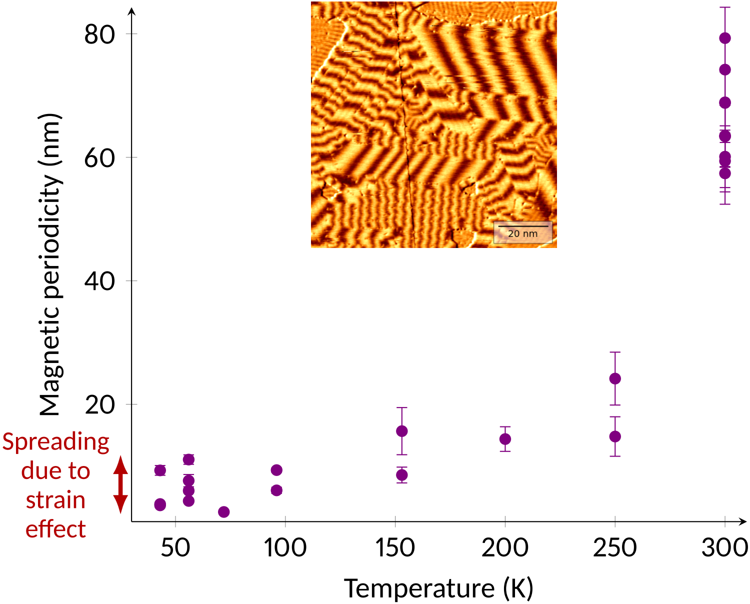
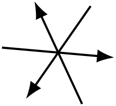
Improvement of the thermal stability, different magnetic state at higher temperatures

Increase of the magnetic periodicity with temperature

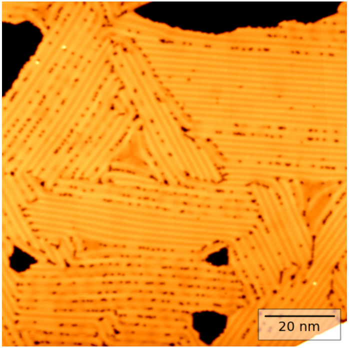


Morphology of the triple layer film

- Nearest neighbor distances mismatch bulk Fe bcc(110)/bulk Ir fcc(111) : 9%
- Reconstruction lines along the 3 equivalent crystallographic directions of the (111) surface



Topography, -700 mV



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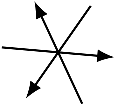

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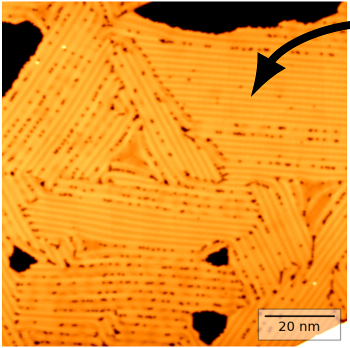

Dense lines

- All identical at every bias
- Spacing between 1.8 and 2.2 nm
- Almost no defects on the lines

Morphology of the triple layer film

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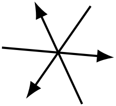
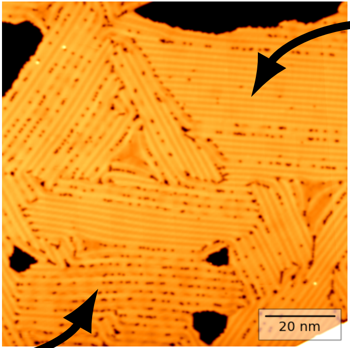


Topography, -700 mV



Double lines

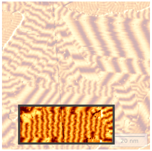
- More defects on the lines
- Spacing between 2.5 and 3.5 nm
- Two types of lines alternating at low positive bias

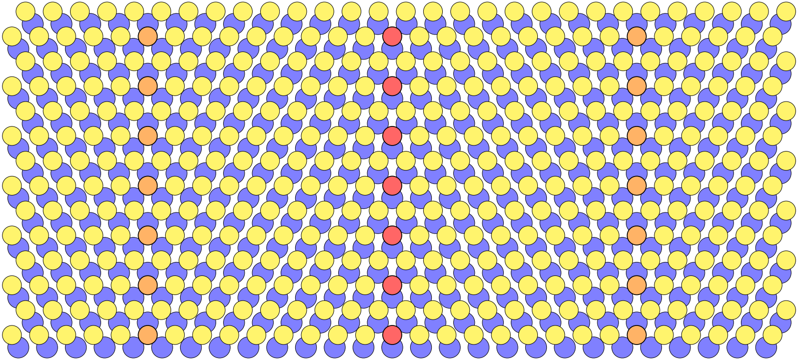
Dense lines

- All identical at every bias
- Spacing between 1.8 and 2.2 nm
- Almost no defects on the lines

Structure model, double lines

- Fe atoms prefer to arrange as a bcc(110) surface
- Lines sitting exactly on top of the DL lines
- At low positive bias, 2 types of lines alternating
- Zigzag wavefront of the spin spirals

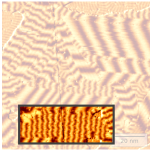




Monolayer   Double layer: bcc compressed   fcc   hcp

S-H Phark *et al.* Reduced-dimensionality-induced helimagnetism in iron nanoislands. *Nature communications* 5 (2014).

Structure model, double lines



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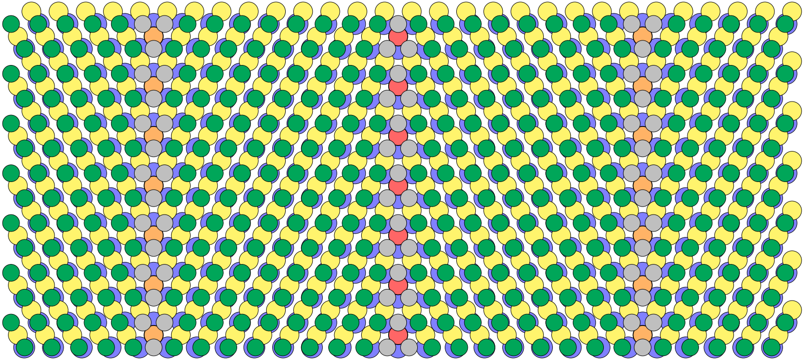

Monolayer   Double layer: bcc compressed   fcc   hcp   Triple layer: bcc   double lines

S-H Phark *et al.* Reduced-dimensionality-induced helimagnetism in iron nanoislands. *Nature communications* 5 (2014).

Structure model, double lines

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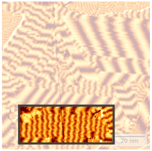

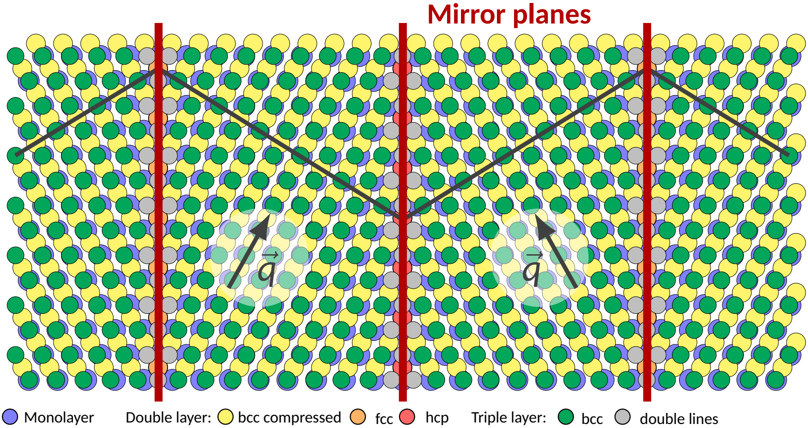

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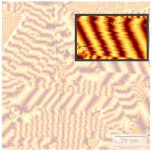
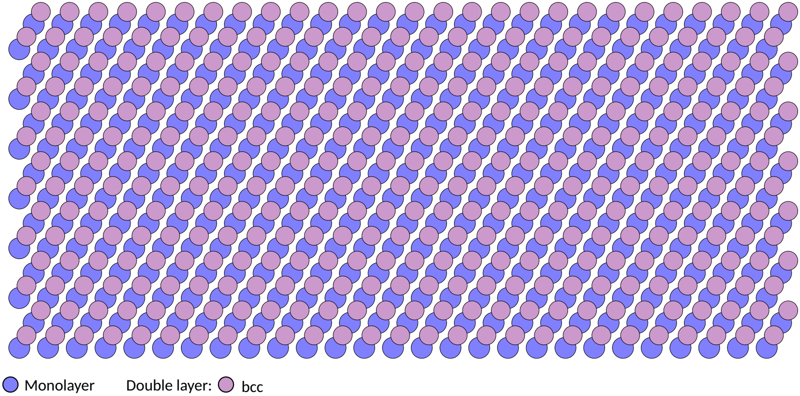
Structure model, dense lines

- Fe atoms prefer to arrange as a bcc(110) surface
- On top of pseudomorphic areas of the double layer, assumed bcc
- All the lines are identical
- Straight but canted wavefront of the spin spirals





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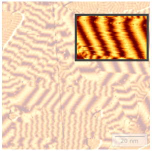

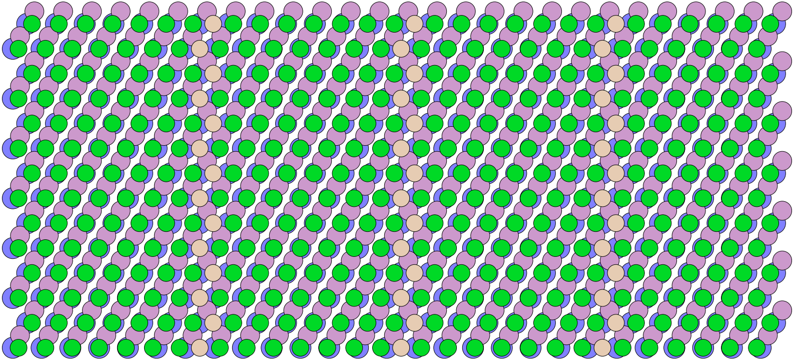

Monolayer Double layer: bcc Triple layer: bcc dense lines

Structure model, dense lines

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- All the lines are identical
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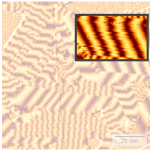
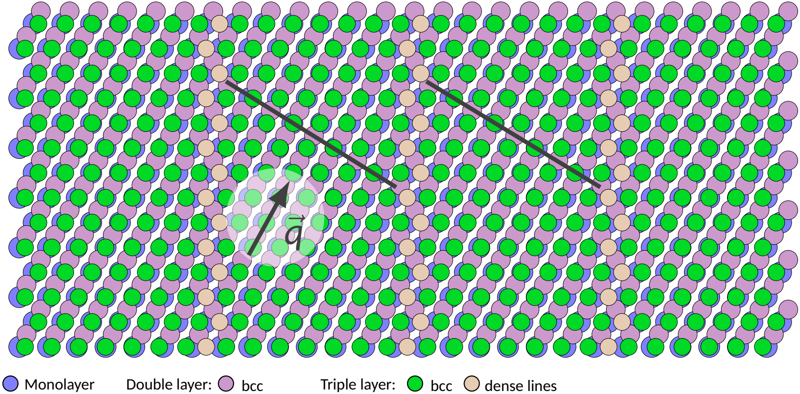
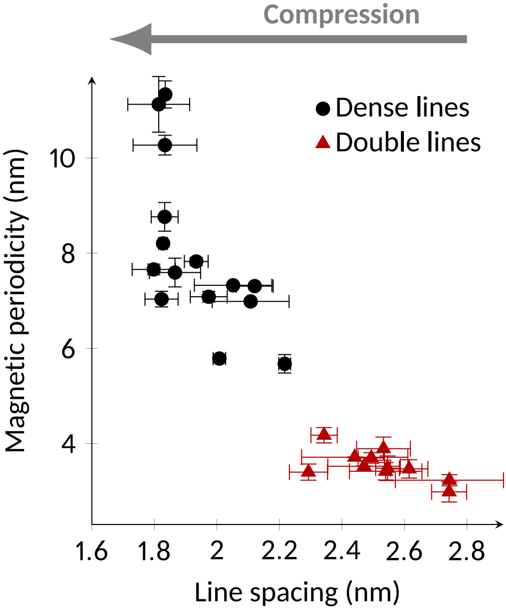
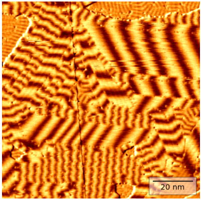


No Mirror plane!



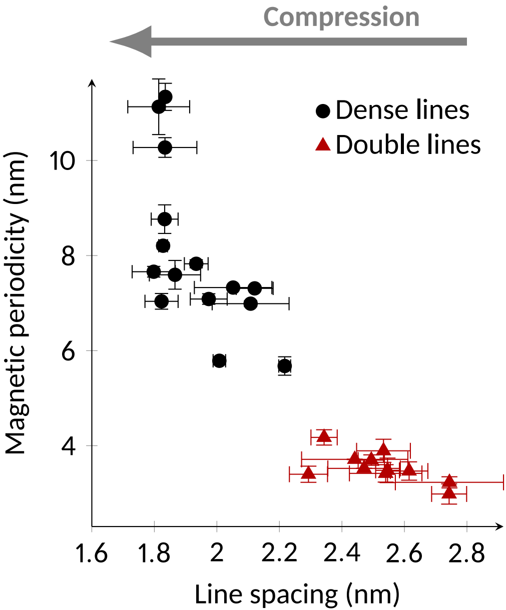
Effect of the strain release on the magnetic periodicity

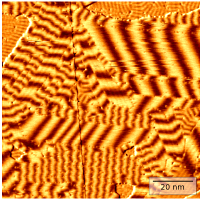




- Measured at low temperature (4 and 8 K)
- Spiral periodicities between 3.5 and 12 nm

Effect of the strain release on the magnetic periodicity





- Measured at low temperature (4 and 8 K)
- Spiral periodicities between 3.5 and 12 nm
- Compression $\nearrow$
  $\Rightarrow$ Magnetic periodicity $\nearrow$

Strong influence of the surface structure on the magnetism

Wavevector and wavefront of the cycloidal
spin spirals completely determined by the local
atom arrangement (at low temperature)

Local changes in the compression of the top layer
(induced by strain release) create local changes
in the spin spirals wavelength

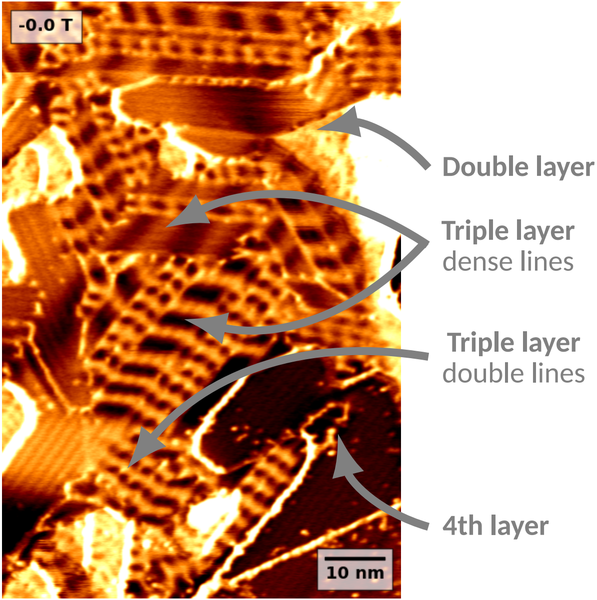
Strong influence of the surface structure on the magnetism

Wavevector and wavefront of the cycloidal spin spirals completely determined by the local atom arrangement (at low temperature)

Local changes in the compression of the top layer (induced by strain release) create local changes in the spin spirals wavelength

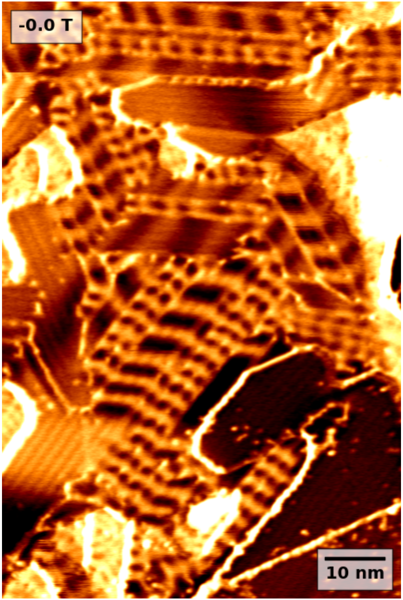
Local fine tuning of the magnetic properties ?

Effect of out-of-plane magnetic field

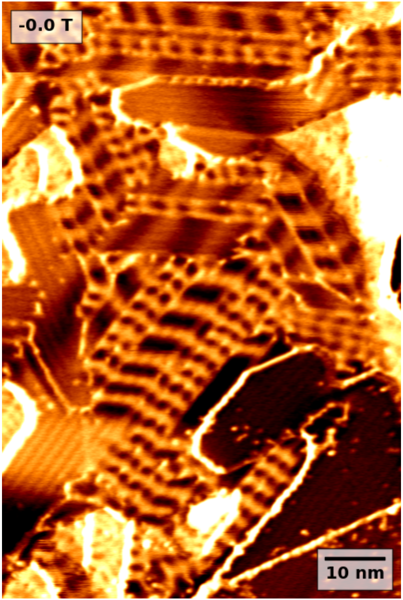


$U = -500\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 4\,\mathrm{K}$

Effect of out-of-plane magnetic field



Effect of out-of-plane magnetic field



4th layer:

- FM state reached at 0.5 T

Triple layer, dense lines:

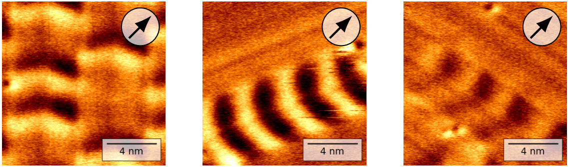
- Dark stripes get thinner, move and disappear
- FM state reached at 2 T

Triple layer, double lines:

- Spirals split up in individual magnetic objects
- These objects are aligned on the reconstruction lines
- They can be isolated around 3 T
- FM state reached around 4 T

Distorted magnetic skyrmions

3Fe/Ir(111)



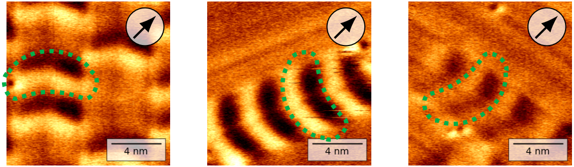
$U = -700\,\text{mV}$, $I = 1\,\text{nA}$, $T = 8\,\text{K}$, $B = -2.5\,\text{T}$

N. Romming *et al.* Writing and deleting single magnetic skyrmions. *Science* 341.6146 (2013).

P-J. Hsu *et al.* Electric field driven switching of individual magnetic skyrmions. *arXiv:1601.02935* (2016).

Distorted magnetic skyrmions

3Fe/Ir(111)



$U = -700\,\text{mV}, I = 1\,\text{nA}, T = 8\,\text{K}, B = -2.5\,\text{T}$

N. Romming *et al.* Writing and deleting single magnetic skyrmions. *Science* 341.6146 (2013).

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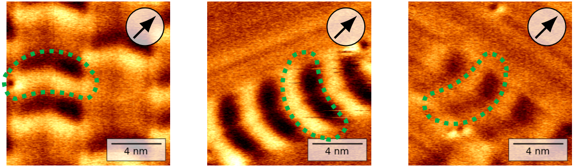

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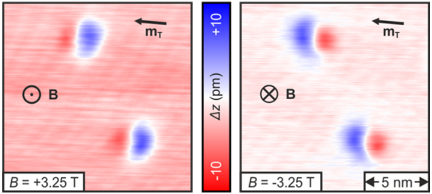
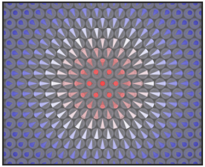
Pd/Fe/Ir(111)



$U = 250\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 4.2\,\mathrm{K}$



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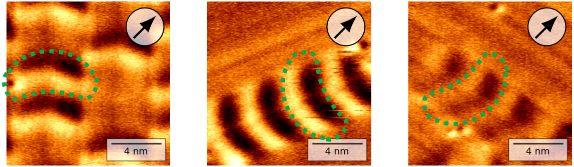

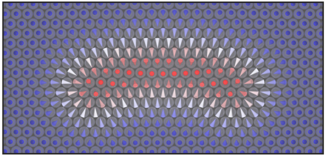

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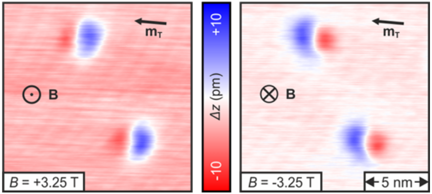

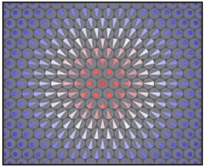

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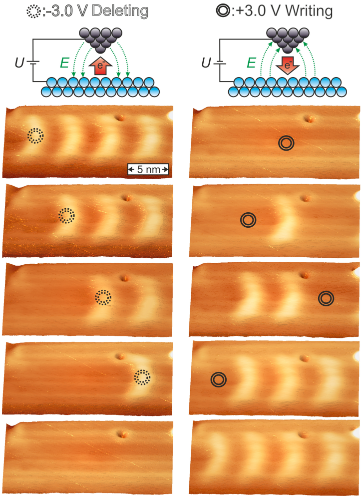
Controlled writing and deleting



$U = 300\,\text{mV}$, $I = 0.5\,\text{nA}$,
$T = 8\,\text{K}$, $B = 2.5\,\text{T}$

Switching with a spin-polarized tip by a voltage ramp

- Deleting with a ramp to $-3\,\text{V}$
- Writing with a ramp to $3\,\text{V}$

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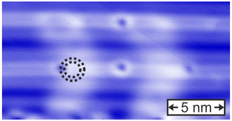
Switching with a W tip



$U = 200\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$,
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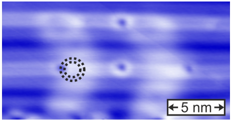
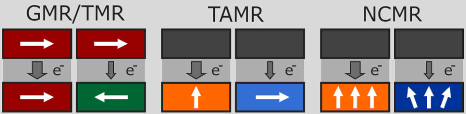


Imaging mechanism:

Non-Collinear MagnetoResistance



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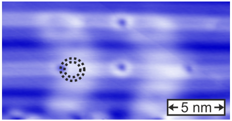

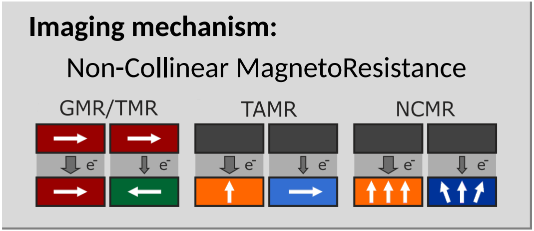

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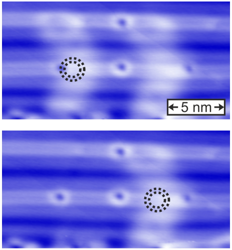

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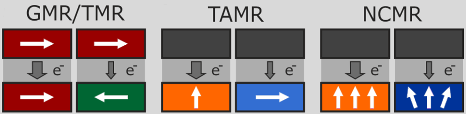

$U = 200\,\text{mV}, I = 1\,\text{nA},$
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Writing
and deleting
with a non magnetic
W tip

$-4\,\text{V}$

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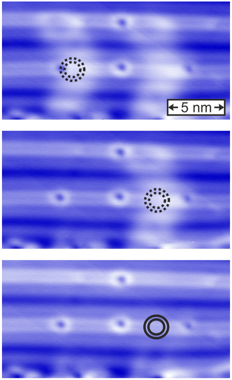

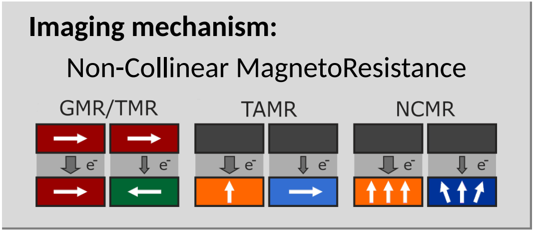

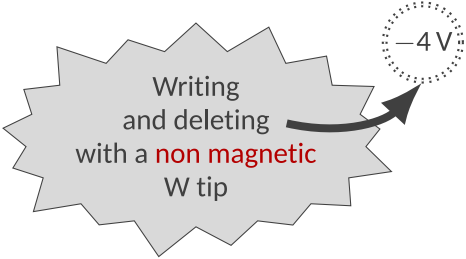

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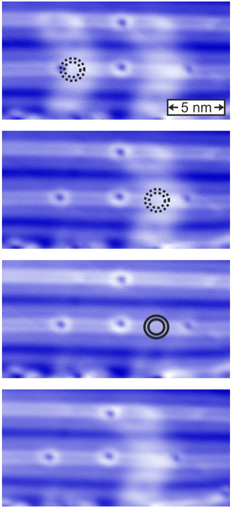

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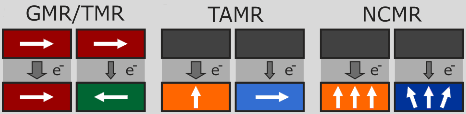

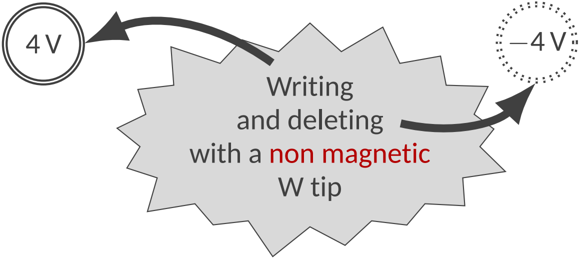

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Electric field driven switching?

Spin-polarized tip
NOT needed

Electric field driven switching?

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NOT needed

Opposite polarity for
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NOT needed

Opposite polarity for
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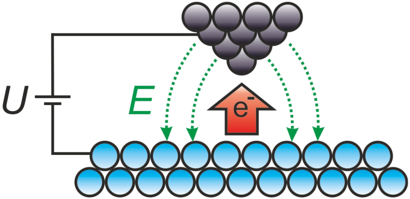
Electric field driven?

Electric field in the STM



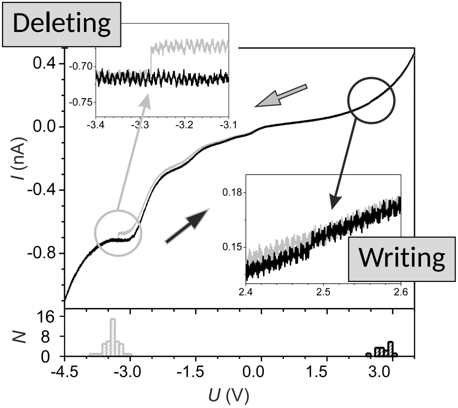
Parallel plates model:

$$\boxed{E = {}^{U}\!/_{d}}$$

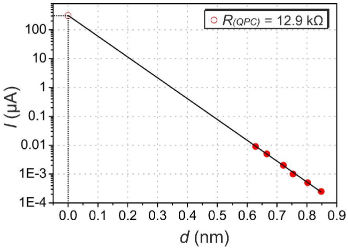
d: tip sample distance

Electric field switching?

How do we measure U?



How do we measure d?



$U = 4\,\mathrm{V}$,
extrapolation to the quantum point contact resistance

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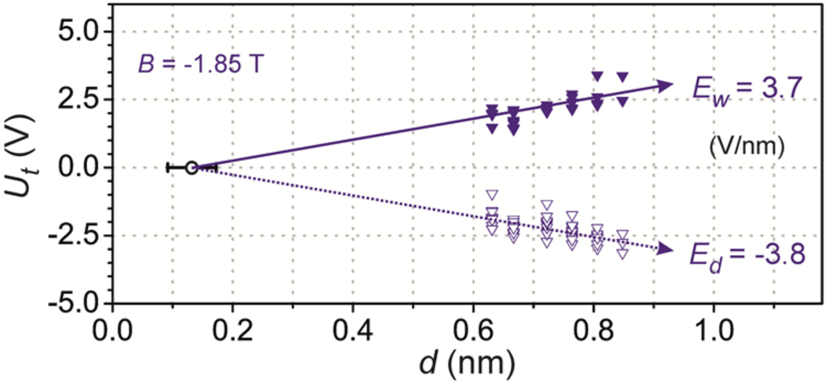
Electric field switching!



- Linear fit with a joint crossing at 0 from the parallel plate model
- E between 1 and 6 $\mathrm{V\,nm^{-1}}$

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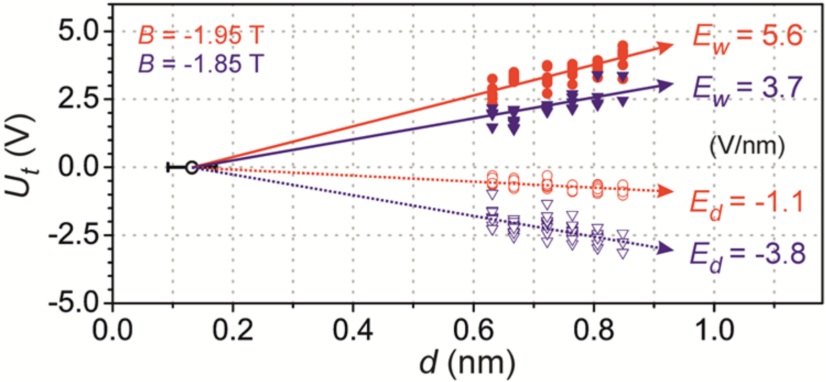

- Linear fit with a joint crossing at 0 from the parallel plate model
- E between 1 and 6 $\mathrm{V\,nm^{-1}}$
- The critical **electric** field depends strongly on the **magnetic** field

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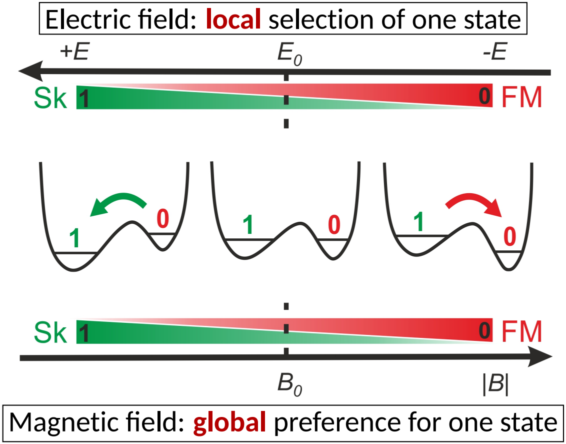
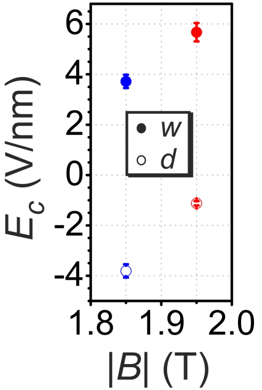
Tuning the energy landscape





$1\,\mathrm{V\,nm^{-1}} \Leftrightarrow 40\,\mathrm{mT}$

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Electric field driven writing and deleting of magnetic skyrmions

Controlled writing and deleting of distorted
single magnetic skyrmions with a non spin polarized STM tip

Proof that electric field is the driving
force for the switching, detailed mechanism
not identified

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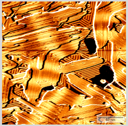
Controlled writing and deleting of distorted single magnetic skyrmions with a non spin polarized STM tip

Proof that electric field is the driving force for the switching, detailed mechanism not identified

Writing and deleting process not based on magnetic field or spin torque but on electric field

Summary

Very strong temperature dependence
of the periodicity of the spin spirals
on the triple layer Fe on Ir(111),
which are **stable up to 300 K**



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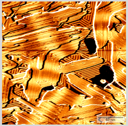
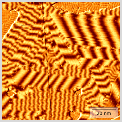


Strain release on the Fe layer on Ir(111)
allowing **fine tuning of the magnetic structure** (wavefront,wavelength of the spirals)



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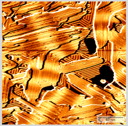

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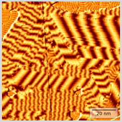
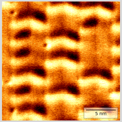


Electric field driven writing and deleting
of single distorted magnetic skyrmions
on the triple layer Fe on Ir(111)



Acknowledgments

Prof. Dr. Roland Wiesendanger
Dr. Kirsten von Bergmann
Dr. André Kubetzka
Dr. Pin-Jui Hsu
Dr. Thomas Eelbo
Niklas Romming
Lorenz Schmidt

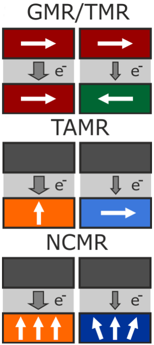
UHH Universität Hamburg

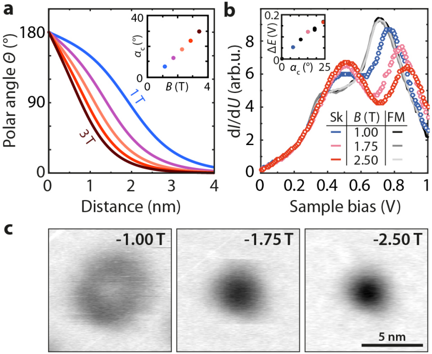
MAGicSky

Funded by the Horizon2020 Framework Programme of the European Union

Non-Collinear MagnetoResistance (NCMR)

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





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Switching with a Cr bulk tip