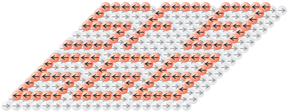
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



MAGic Sky

Funded by the Horizon2020 Framework Programme of the European Union

Electric field induced switching of magnetic skyrmions and strain relief effects

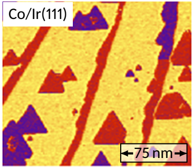
Aurore Finco, Pin-Jui Hsu, Niklas Romming, André Kubetzka, Kirsten von Bergmann and Roland Wiesendanger

University of Hamburg

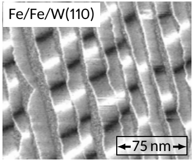
Non-collinear magnetism in ultrathin films

Small scale complex magnetic structures can be stabilized in ultrathin films by the competition between:

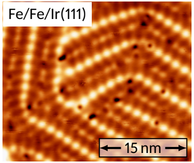
- Exchange interaction, possibly with frustration
- Dzyaloshinskii-Moria interaction (DMI), induced by the symmetry breaking at the interface
- Anisotropy
- Dipolar interaction
- Higher order interactions (biquadratic, 4-spin, ...)



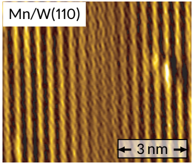
Ferromagnetic islands



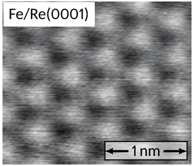
Chiral domain walls



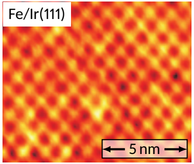
Spin spirals



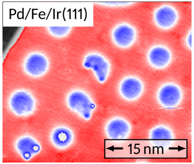
AFM spin spirals



Néel state



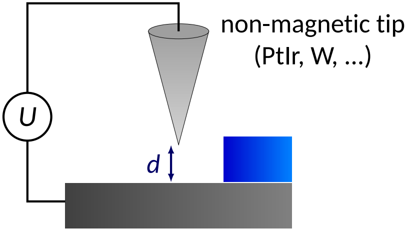
Nanoskyrmion lattice



Isolated skyrmions

Spin-polarized scanning tunneling microscopy

STM

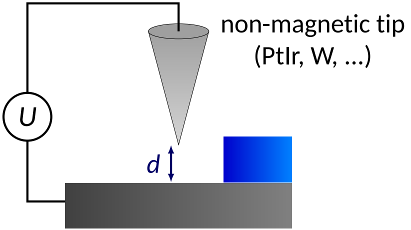


$$\boxed{I_0 \propto e^{-\kappa d}}$$

R. Wiesendanger. Spin mapping at the nanoscale and atomic scale. *Reviews of Modern Physics* 81.4 (2009), pp. 1495–1550.

Spin-polarized scanning tunneling microscopy

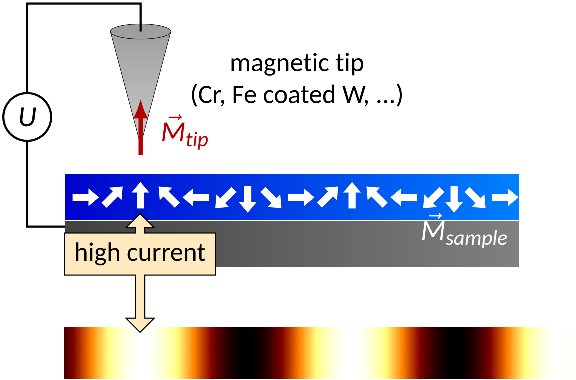
STM



$$I_0 \propto e^{-\kappa d}$$

SP-STM

Tunneling MagnetoResistance



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

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Spin-polarized scanning tunneling microscopy

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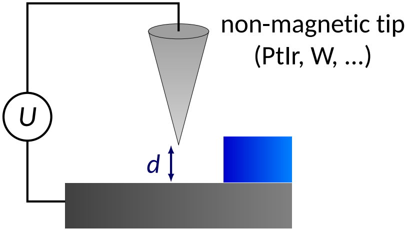

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SP-STM

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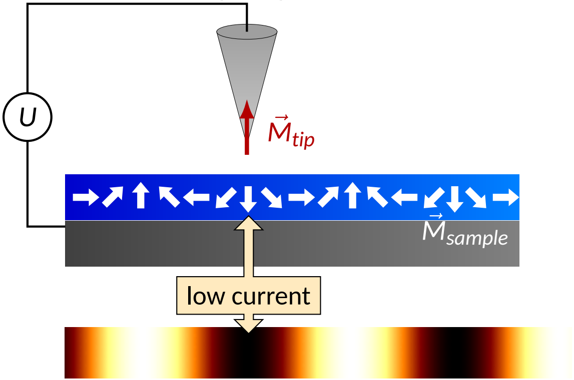

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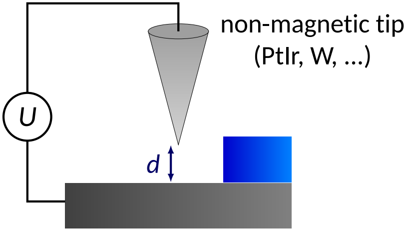


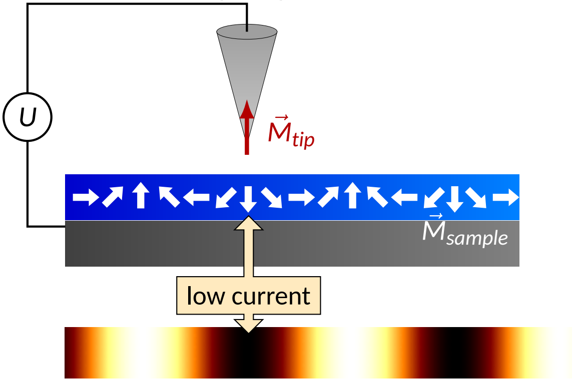
$$I_0 \propto e^{-\kappa d}$$

Imaging of the 3D spin structure
down to the atomic scale

Manipulation of the magnetic state

SP-STM

Tunneling MagnetoResistance



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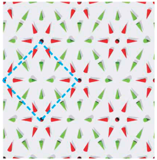
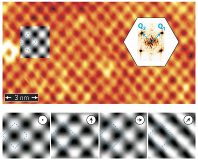
The Fe/Ir interface

- 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), pp. 713–718.

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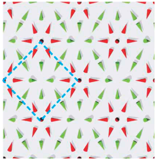
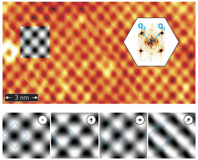
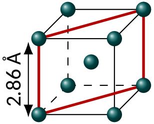


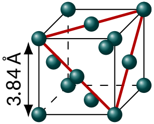


Bulk Fe: bcc



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

Bulk Ir: fcc



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

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

P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116.1 (2016), p. 017201.

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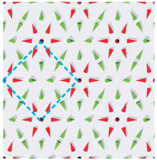

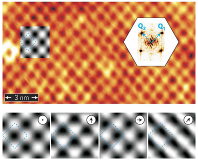

- Strong DMI, about 1.8 meV per atom.
  - Nanoskyrmion lattice in the monolayer Fe.

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), pp. 713–718.

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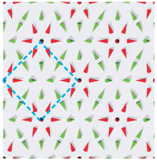
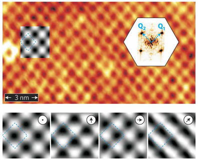




- Strong DMI, about 1.8 meV per atom.
  - Nanoskyrmion lattice in the monolayer Fe.

Bulk Fe: bcc **Bulk Ir: fcc**

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

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

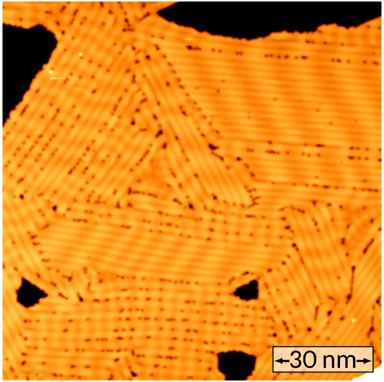
- Large strain on the Fe film.
  - Formation of dislocation lines, guiding spin spirals in the double layer Fe.

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

P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Physical Review Letters* 116.1 (2016), p. 017201.

The triple layer Fe on Ir(111)

Constant current map

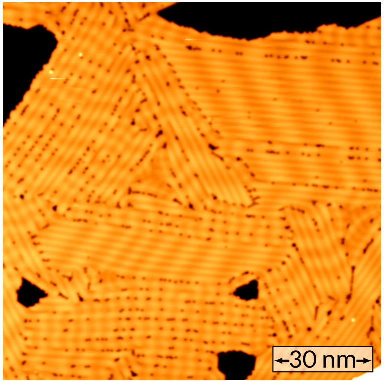


−700 mV, 1 nA, 8 K, Cr bulk tip

- Strain relieved by dislocation lines along the high symmetry directions

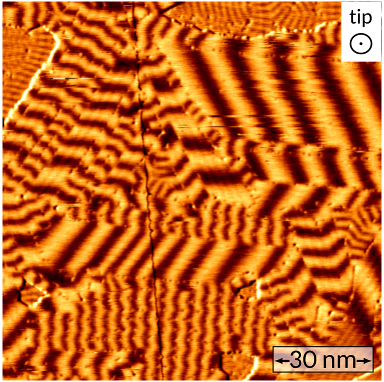
The triple layer Fe on Ir(111)

Constant current map



−700 mV, 1 nA, 8 K, Cr bulk tip

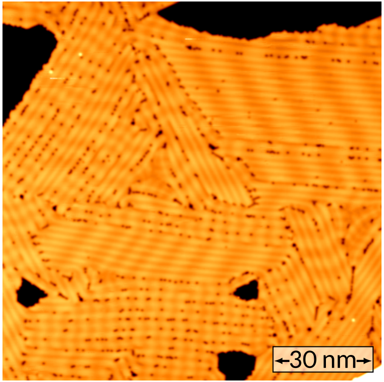
Differential conductance map



- Strain relieved by dislocation lines along the high symmetry directions
- Spin spirals propagate along the dislocation lines

The triple layer Fe on Ir(111)

Constant current map



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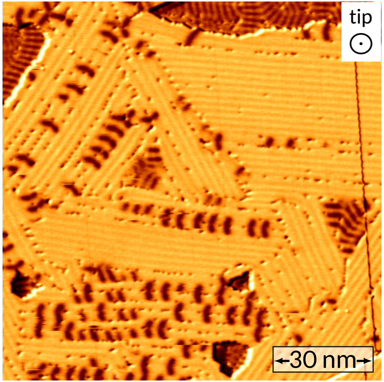
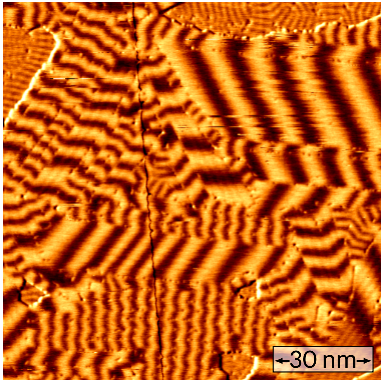


2.5 T

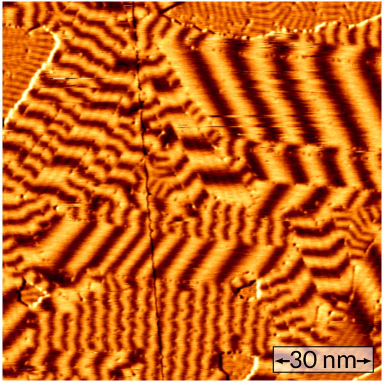
- Strain relieved by dislocation lines along the high symmetry directions
- Spin spirals propagate along the dislocation lines
- Skyrmions appear in external magnetic field

Outline



- Why do all the spirals look so different?
  - The strain relief is affecting the magnetic state

Outline



- Why do all the spirals look so different?
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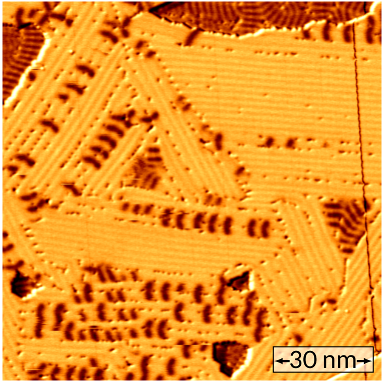
- What happens when the sample is warmed up to room temperature?

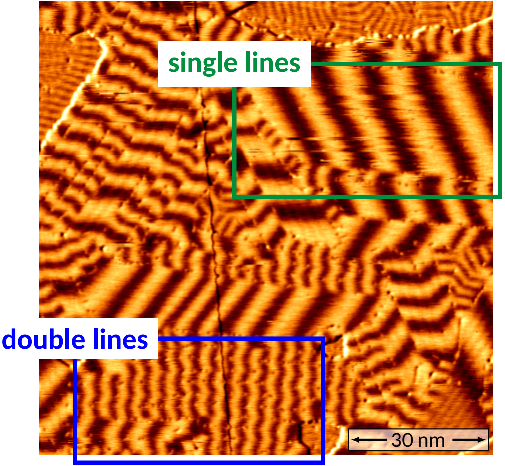
Outline



- Why do all the spirals look so different?
  - The strain relief is affecting the magnetic state
- What happens when the sample is warmed up to room temperature?
- The skyrmions can be switched by electric field

Coexistence of double and single lines

Differential conductance

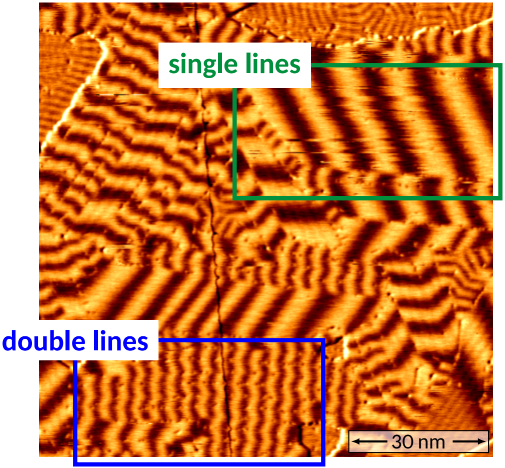


−700 mV, 1 nA, Cr bulk tip, 8 K, 0 T

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

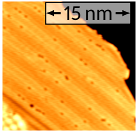
Coexistence of double and single lines

Differential conductance



−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

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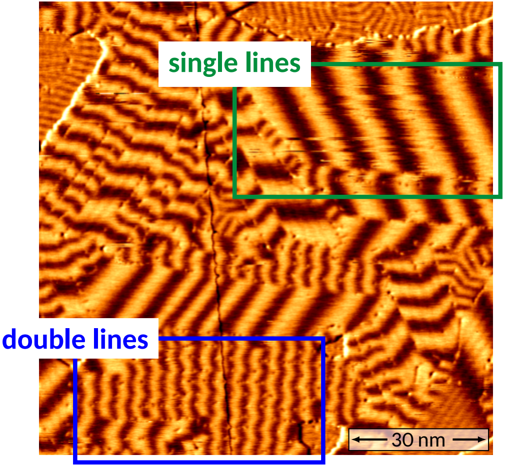
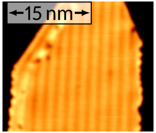
Differential conductance



−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



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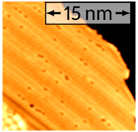

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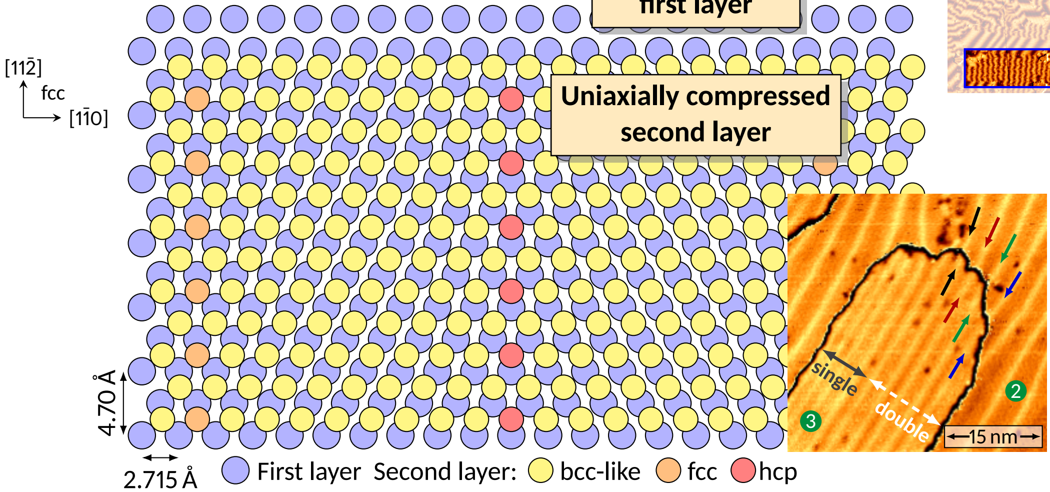
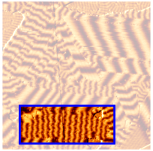
Double lines, structure model





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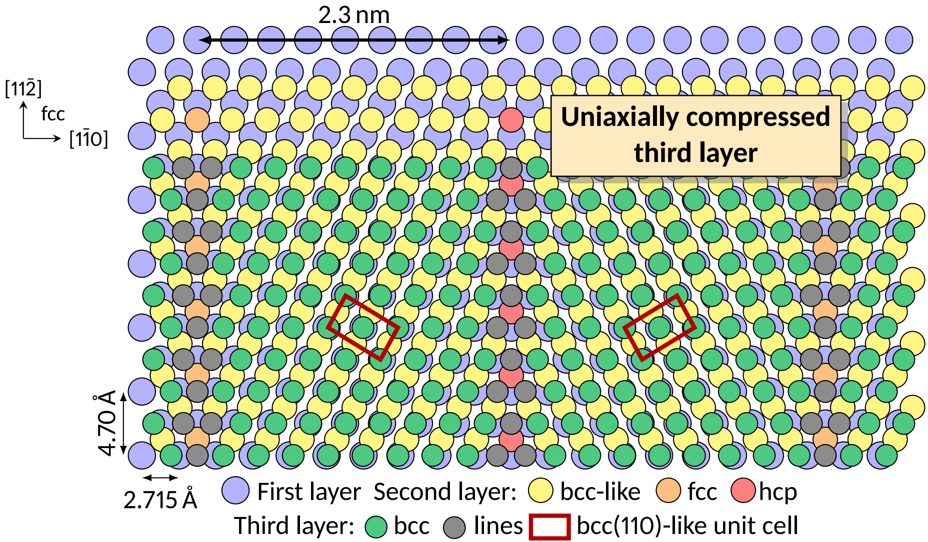

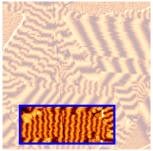

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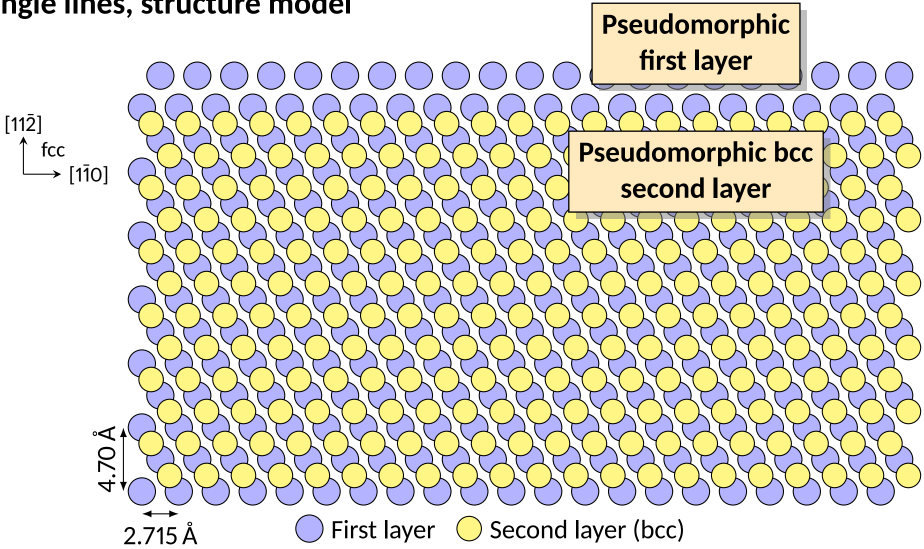

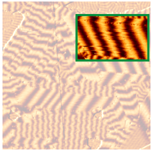

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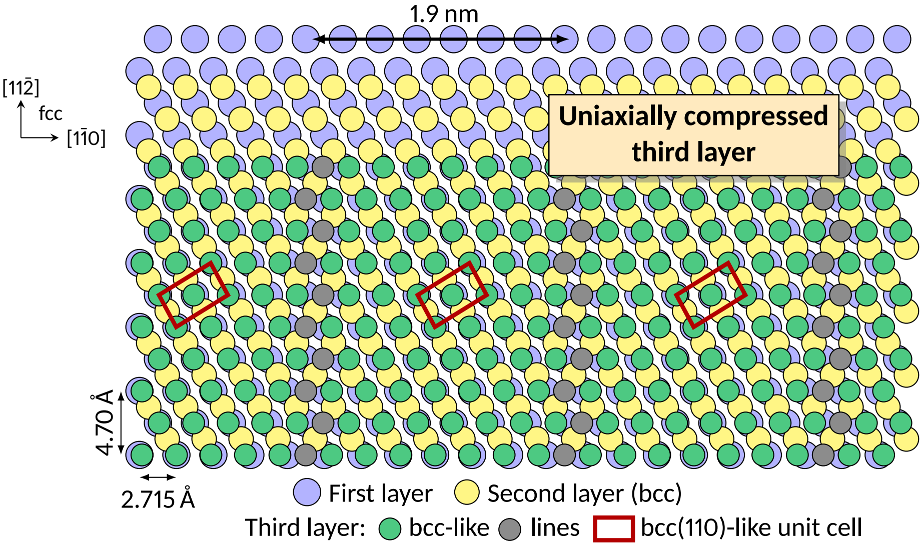

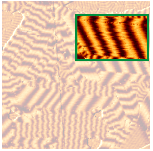

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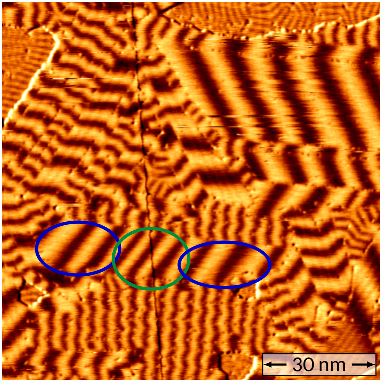
Varying spin spiral period



Dislocation lines spacing:

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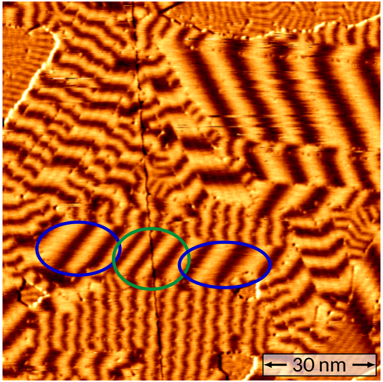
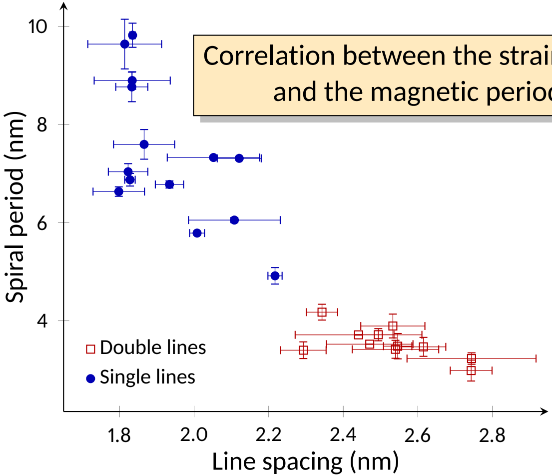
Varying spin spiral period





Correlation between the strain relief and the magnetic 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), p. 214402.

Simple micromagnetic model

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

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

Simple micromagnetic model

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Which parameters are modified by the strain relief?

- DMI?:
- Anisotropy?:
- Exchange coupling?

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Simple micromagnetic model

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

Which parameters are modified by the strain relief?

- DMI?: comes mostly **from the interface** (not affected by the strain relief), **should not be the dominant effect**
- Anisotropy?:
- Exchange coupling?

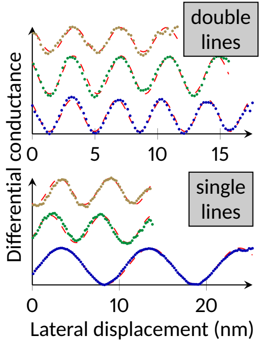
A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *Journal of Magnetism and Magnetic Mat.* 138.3 (1994), pp. 255–269.

Simple micromagnetic model

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

Which parameters are modified by the strain relief?

- DMI?: comes mostly **from the interface** (not affected by the strain relief), **should not be the dominant effect**
- Anisotropy?: The spirals are homogeneous, **the anisotropy is neglected.**
- Exchange coupling?



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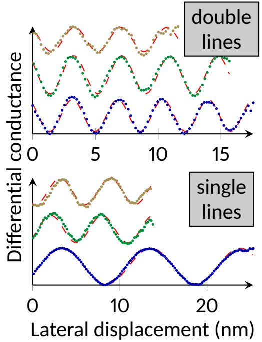
  Spin spiral period $\lambda = 4\pi \frac{A}{|D|}$ (with $K_{\mathrm{eff}} = 0$)

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

$$\boxed{3\,\mathrm{nm} \leqslant \lambda \leqslant 10\,\mathrm{nm}}$$
$$\updownarrow$$
$$\boxed{0.6\,\mathrm{pJ\,m^{-1}} \leqslant A \leqslant 2.2\,\mathrm{pJ\,m^{-1}}}$$



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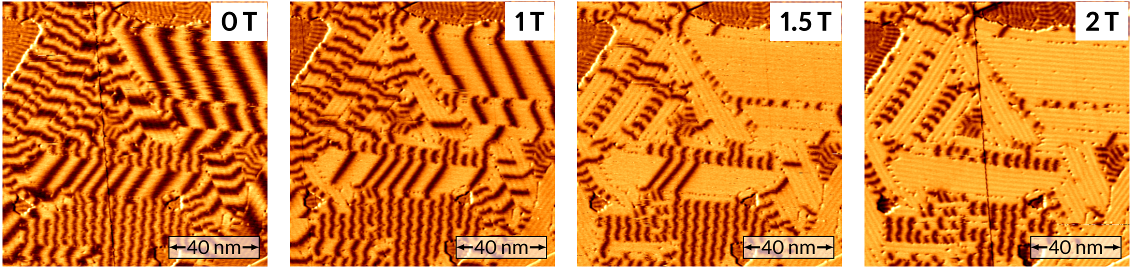
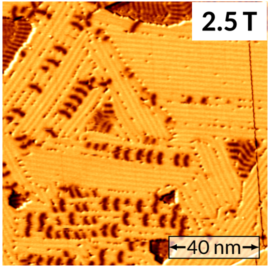
Magnetic phase transition

Differential conductance maps, out-of-plane sensitive tip

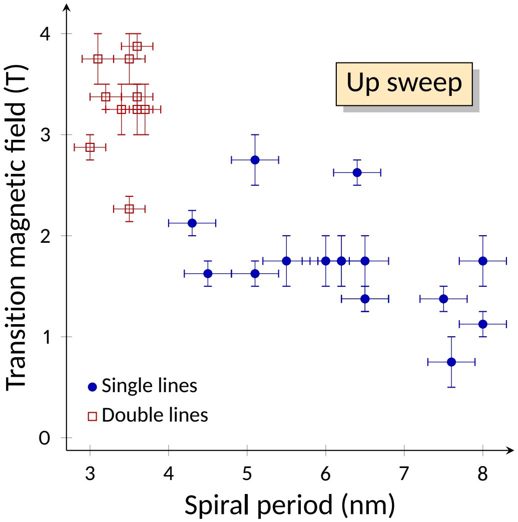


−700 mV, 1 nA, 8 K, Cr bulk tip



- 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



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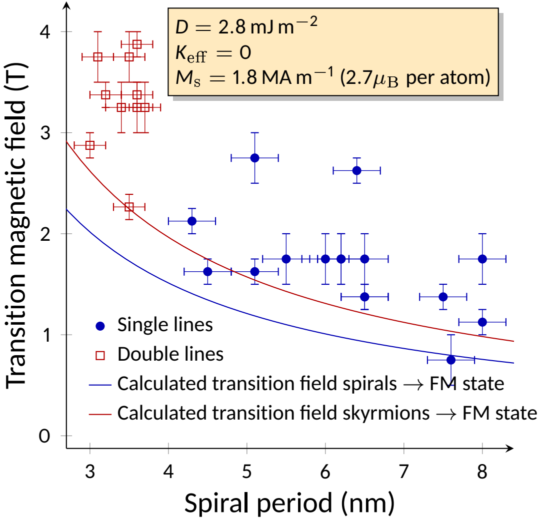

Back to the model, with a Zeeman term:

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

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

$$h_{\mathrm{t}}^{\mathrm{spiral}}(K_{\mathrm{eff}} = 0) = 0.308$$
$$h_{\mathrm{t}}^{\mathrm{skyrmion}}(K_{\mathrm{eff}} = 0) = 0.401$$

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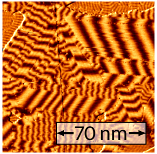
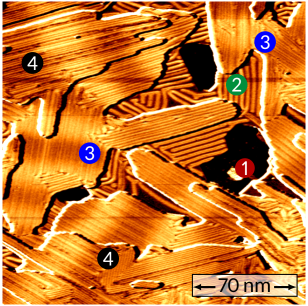
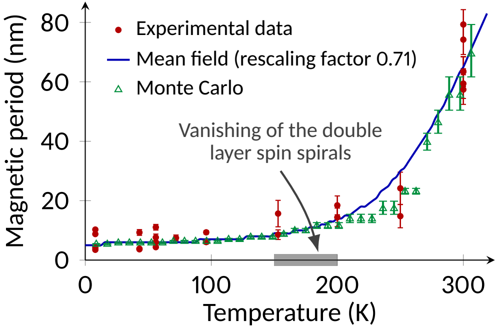
Temperature-induced increase of the spiral periods

Collaboration with Levente Rózsa and Elena Vedmedenko

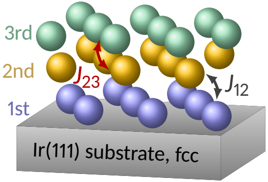




−500 mV, 3 nA, **300 K**, Cr bulk tip, 0 T



- **Different parameters in the 3 layers.**
- 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.**



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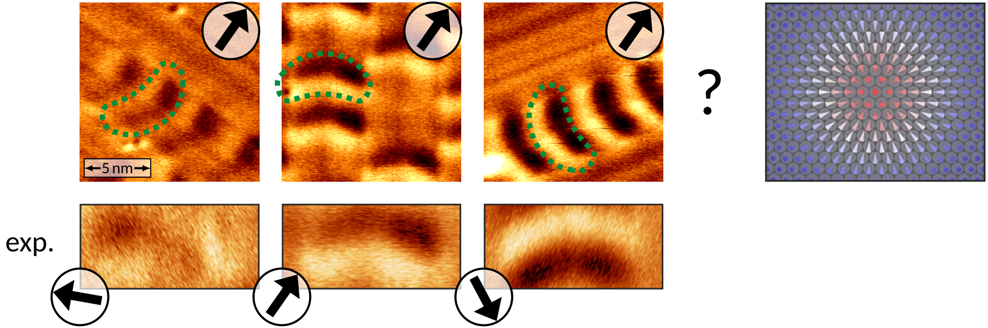
Skyrmions



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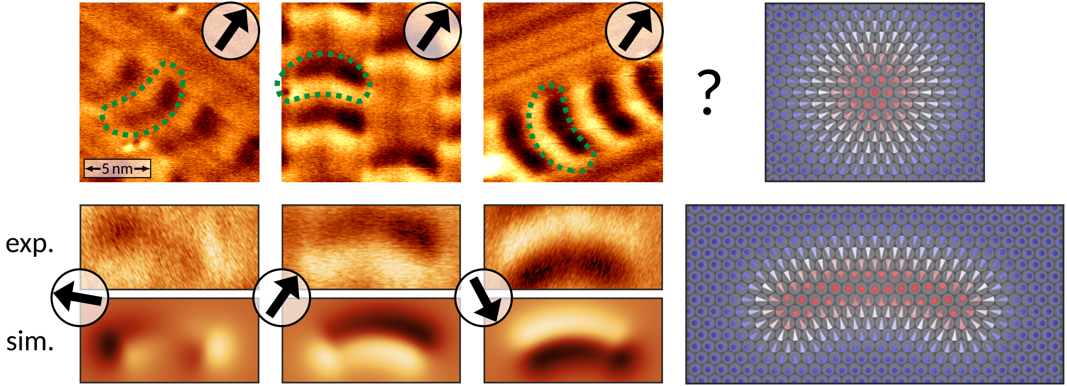

- In-plane sensitive measurements allow to determine the full 3D spin structure
- Same topology as the round skyrmions, but distorted by the surface structure

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

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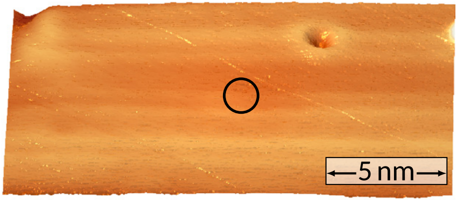

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Switching mechanism?

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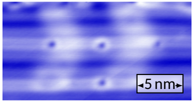
Also with non-magnetic tips!



200 mV, 1 nA, 8 K, −1.85 T, W tip

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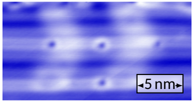

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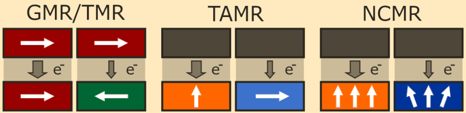
Imaging mechanism:

Non-Collinear MagnetoResistance



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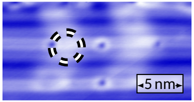

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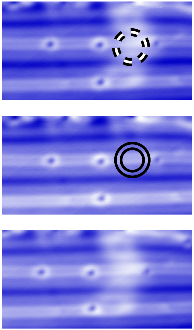

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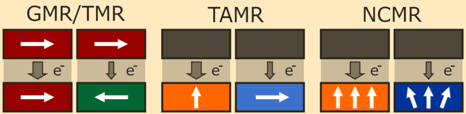

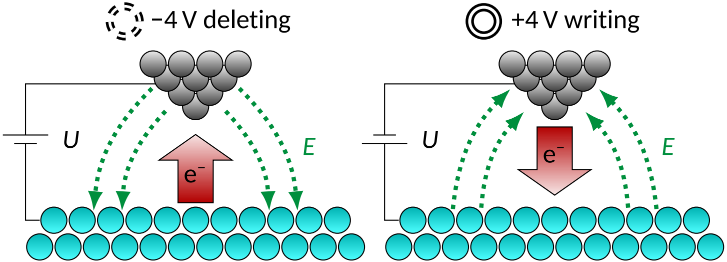

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- Spin-polarized tip **not** needed
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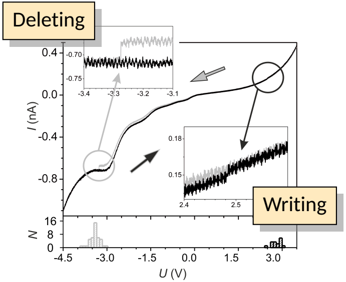

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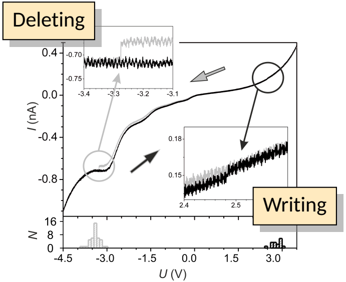

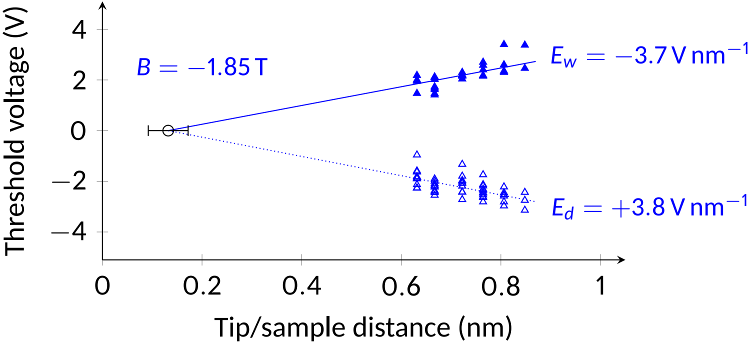

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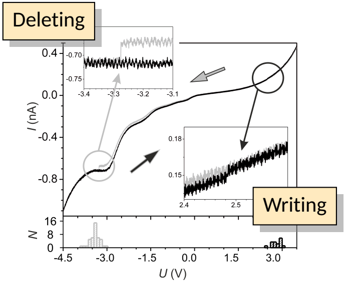
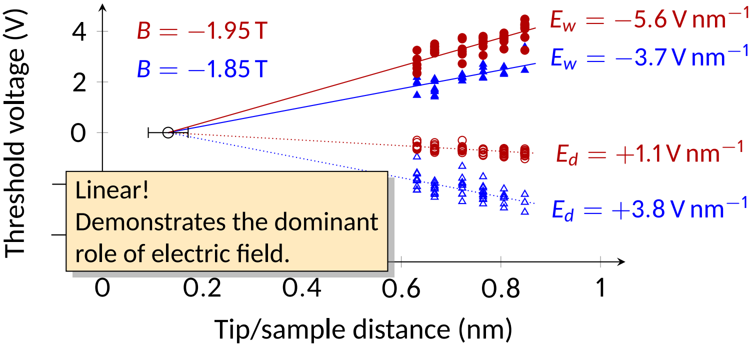




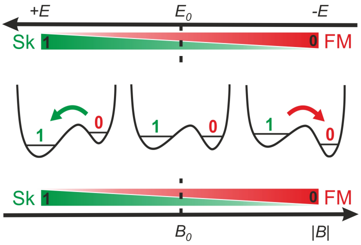
Linear!
Demonstrates the dominant role of electric field.

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

Summary

- The strain relief in the triple layer Fe on Ir(111) is tuning the spin spirals (shape and period), mainly via the exchange coupling.
- The period of the spin spirals is remarkably **increased by temperature**.

Electric field: **local** selection of one state



Magnetic field: **global** preference for one state

- Skyrmions are created in external magnetic field and they can be reliably switched with electric field
- $1\,\mathrm{V\,nm^{-1}} \sim 40\,\mathrm{mT}$
- Combined with NCMR for detection, **all electrical read/write unit**.

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

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

Acknowledgements

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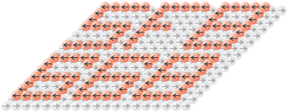
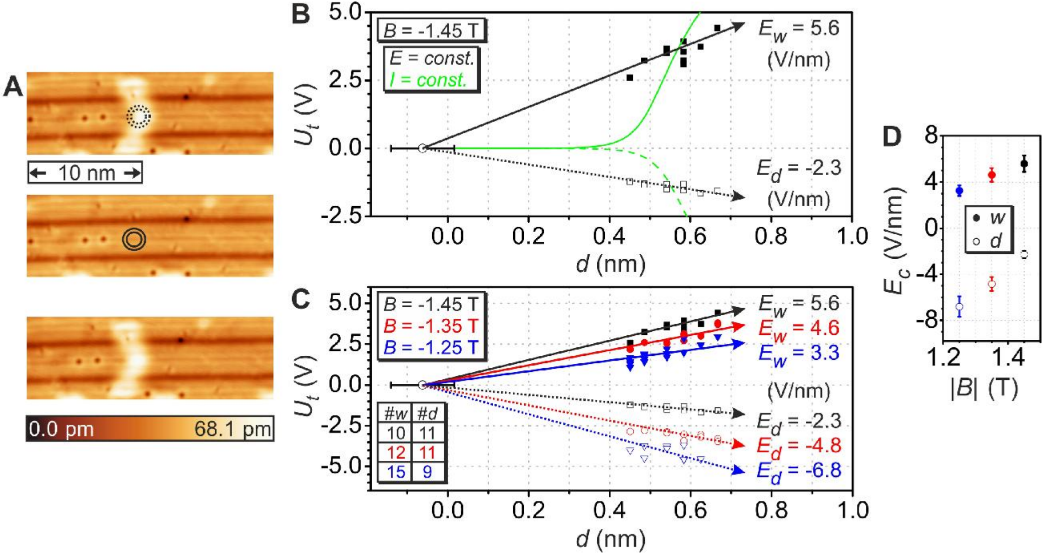
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



MAGicSky

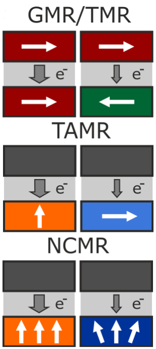
Funded by the Horizon2020 Framework Programme of the European Union

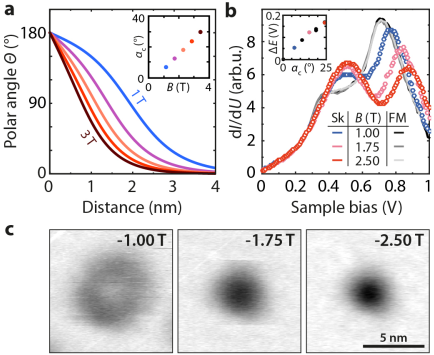
Switching with a Cr bulk tip



Noncollinear 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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