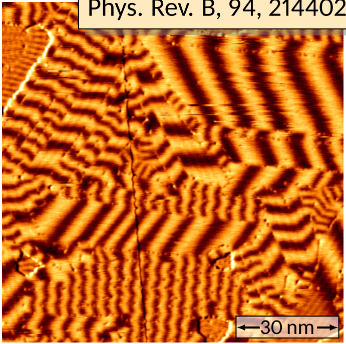
Universität Hamburg

MA 22.8: Tailoring non-collinear magnetism by misfit dislocation lines

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

University of Hamburg

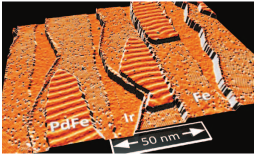
Phys. Rev. B, 94, 214402 (2016)



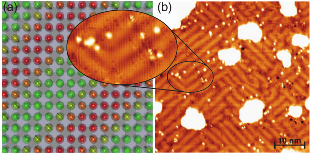
Why do all the spin spirals look so different?

Examples of spin spirals in ultrathin films

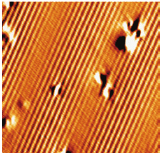
Pd/Fe/Ir(111)



Mn/W(001)



Mn/W(110)



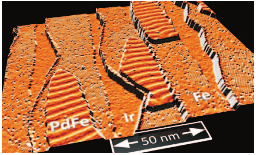
N. Romming *et al.* Writing and Deleting Single Magnetic Skyrmions. *Science* 341.6146 (2013).

K. von Bergmann *et al.* Interface-induced chiral domain walls, spin spirals and skyrmions revealed by SP-STM. . *J. Phys.: Condens. Matter* 26.39 (2014).

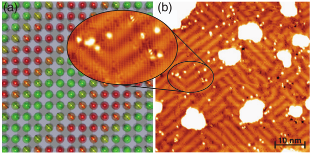
Why do all the spin spirals look so different?

Examples of spin spirals in **pseudomorphic** ultrathin films

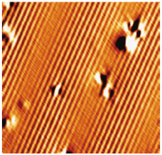
Pd/Fe/Ir(111)

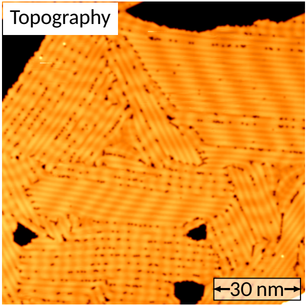


Mn/W(001)



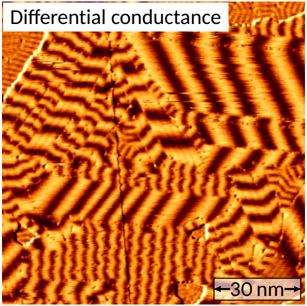
Mn/W(110)





Reconstructed film

Non spatially uniform properties!



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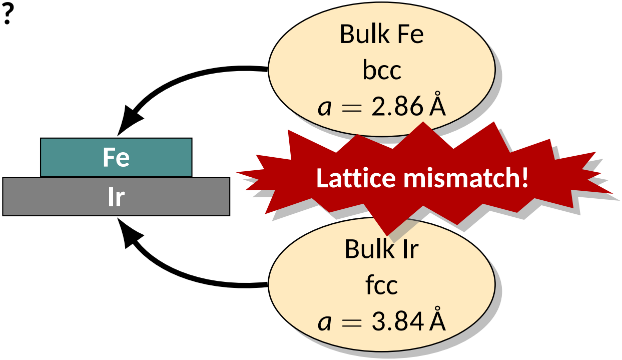
What are these lines?



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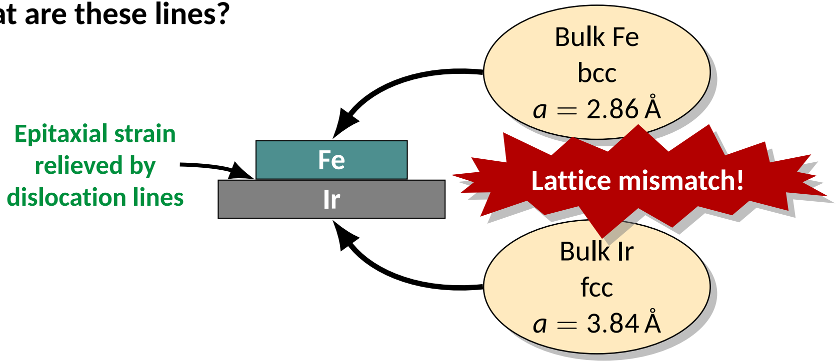
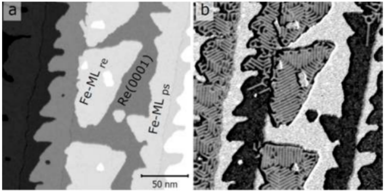
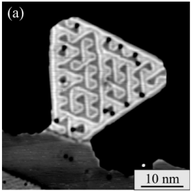


Fe/Re(0001)



Ni/Fe/Ir(111)



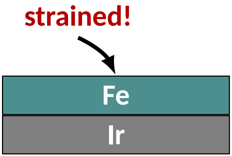
A. Palacio-Morales *et al.* Coupling of Coexisting Noncollinear Spin States in the Fe ML on Re(0001). *Nano Lett.* (2016).

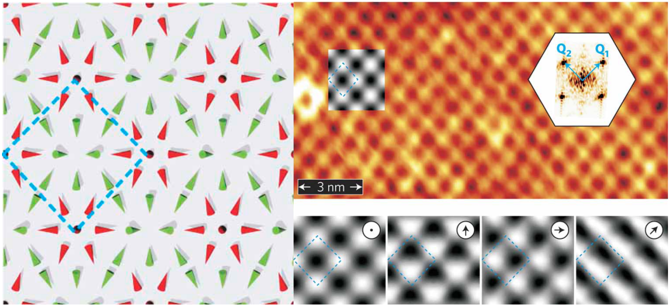
D. Iaia *et al.* Structural and magnetic properties of Ni/Fe nanostructures on Ir(111). *Phys. Rev. B* 93.13 (2016).

What is the structure of the Fe film?

Monolayer Fe on Ir(111)

- Grows pseudomorphically
- Nanoskyrmion lattice, 1 nm period



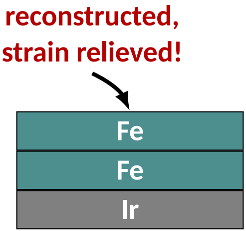


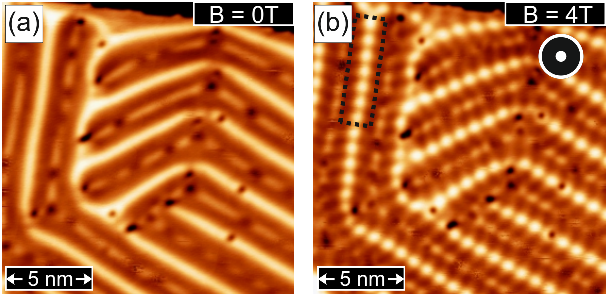
S. Heinze *et al.* Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nat. Phys.* 7.9 (2011).

What is the structure of the Fe film?

Double layer Fe on Ir(111)

- Exhibits dislocation lines
- Spin spirals along the lines
- 1.6 nm period

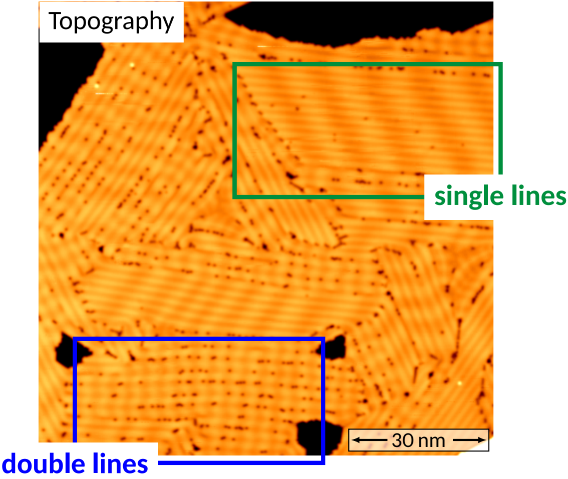




P.-J. Hsu *et al.* Guiding Spin Spirals by Local Uniaxial Strain Relief. *Phys. Rev. Lett.* 116.1 (2016).

What is the structure of the Fe film?

Two types of dislocation line areas in the triple layer Fe on Ir(111)



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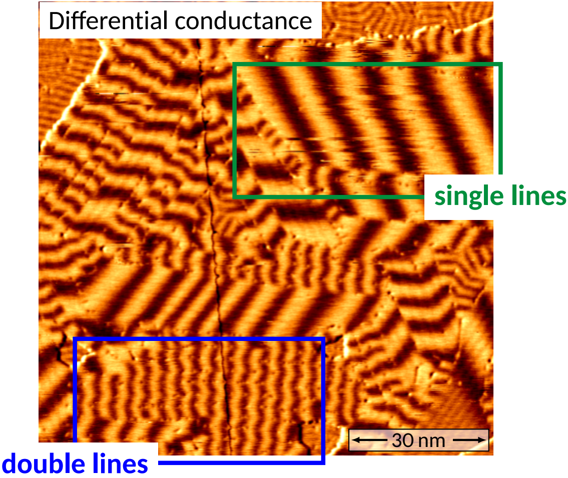

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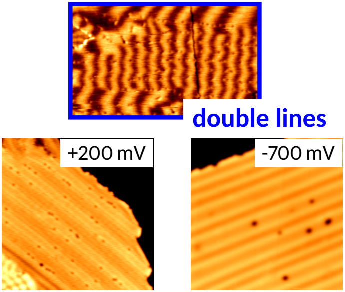
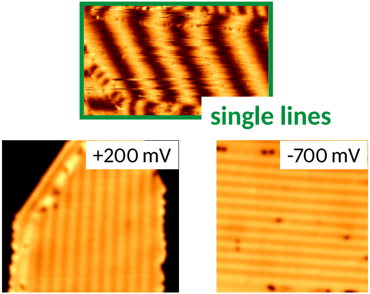
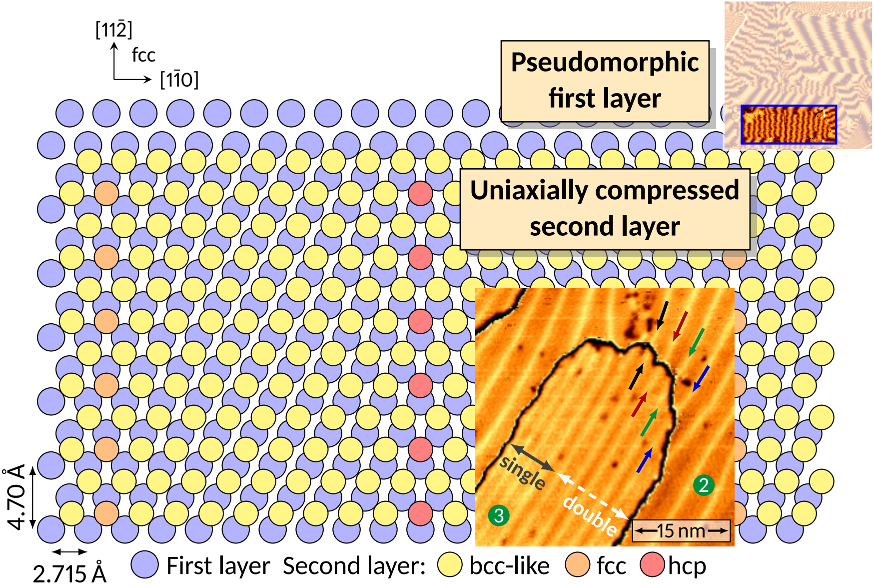


- Double line feature only at positive bias
- Line spacing 2.2 to 2.8 nm
- Spin spiral period 3 to 4 nm
- Zigzag wavefront



- 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 wavefront

Atomic structure model for the double line regions



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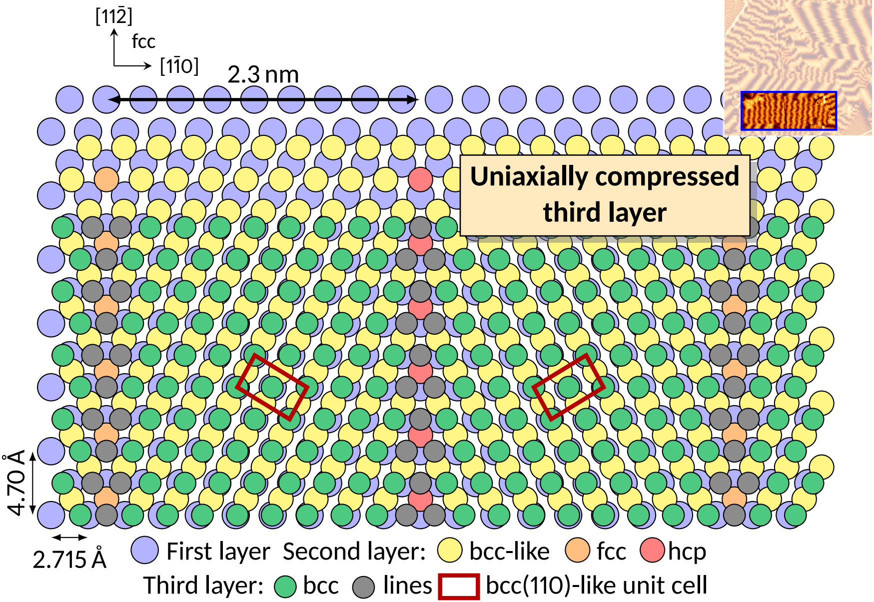
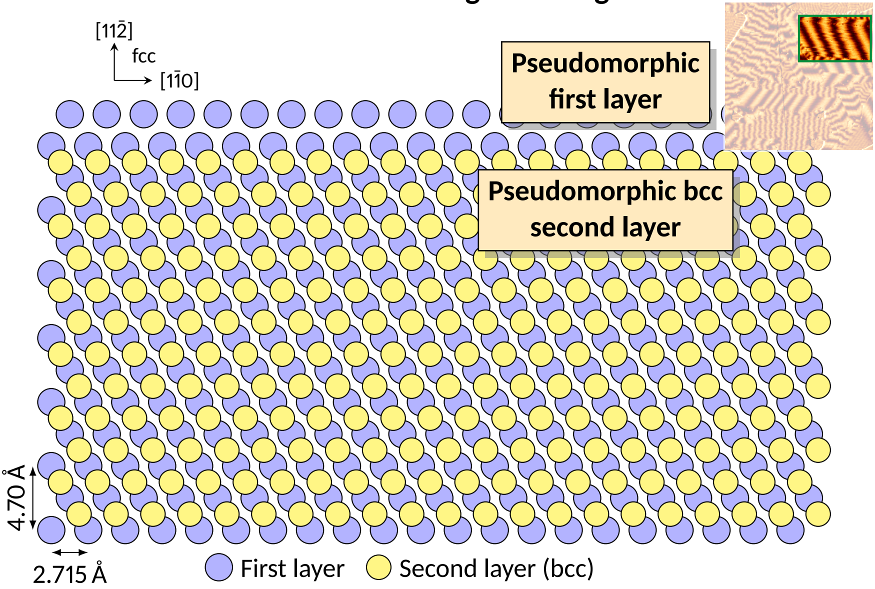
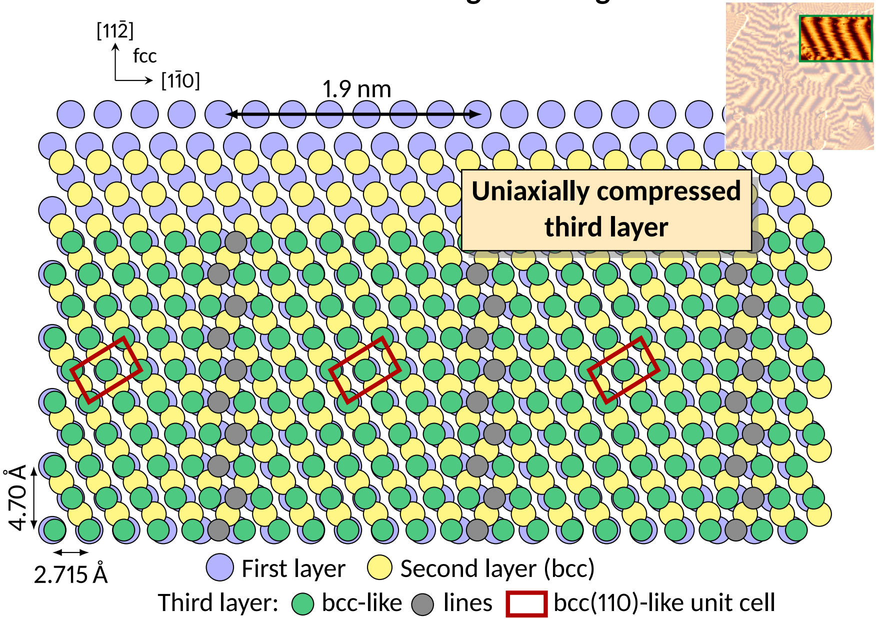


Atomic structure model for the single line regions

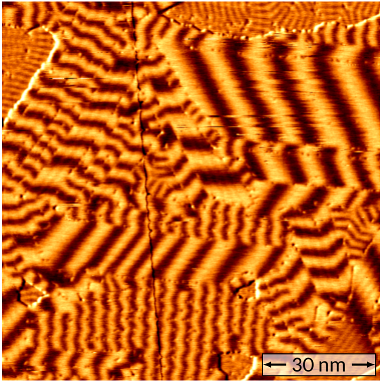


Atomic structure model for the single line regions



Why do all the spin spirals look so different?

- The Fe film is reconstructed
- There is even two types of regions with dislocation lines
- These lines are created to relieve the epitaxial strain in the film



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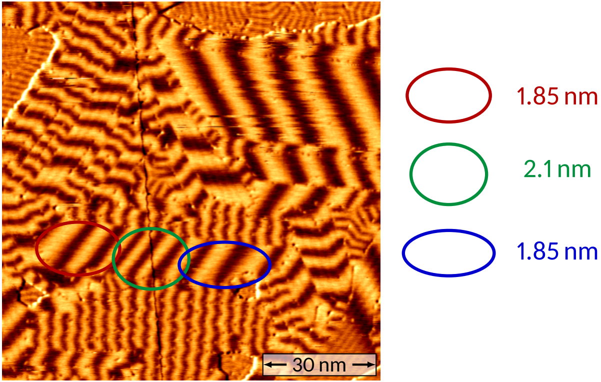
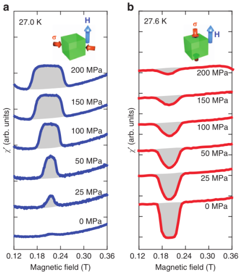


The variations of the strain relief induce variations of the magnetic state.

Does strain influence non-collinear magnetism?

Mechanical strain

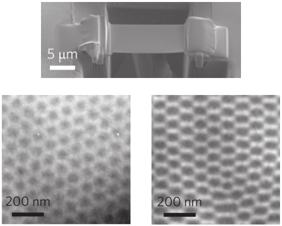
MnSi



⇓

Anisotropy

FeGe



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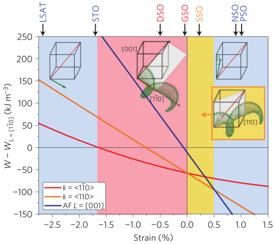
DMI

Epitaxial strain

$BiFeO_3$



⇓

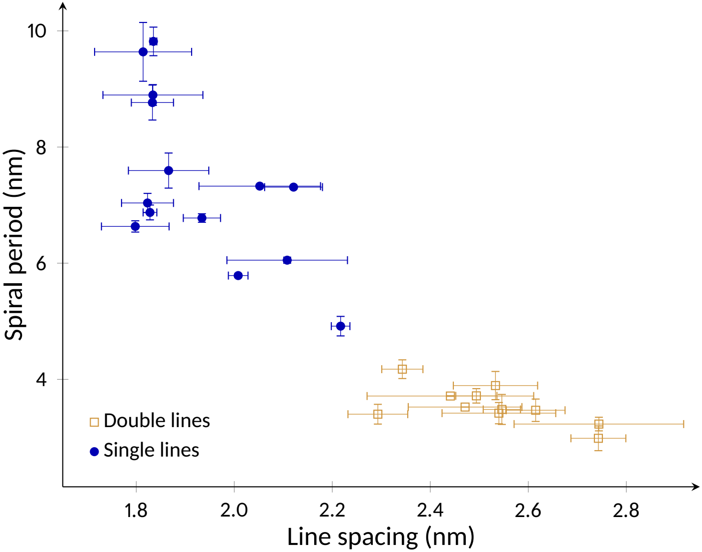
Anisotropy

Y. Nii *et al*. Uniaxial stress control of skyrmion phase. *Nat. Commun.* 6 (2015).

K. Shibata *et al*. Large anisotropic deformation of skyrmions in strained crystal. *Nat. Nano.* 10.7 (2015).

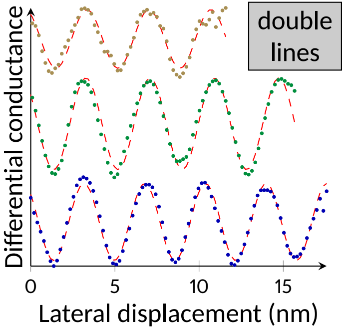
D. Sando *et al*. Crafting the magnonic and spintronic response of $BiFeO_3$ films by epitaxial strain. *Nat. Mater.* 12.7 (2013).

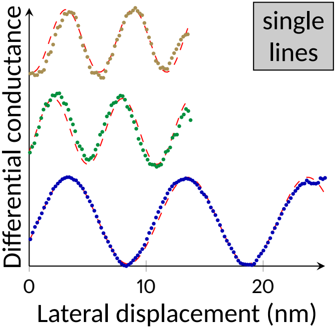
Dependence of the spin spiral period on the spacing between the lines



Anisotropy, DMI, exchange coupling?

- The Dzyaloshinskii-Moriya interaction comes mostly from the interface, **the effect should be small**.
- The effective magnetic anisotropy seems to be negliglible:





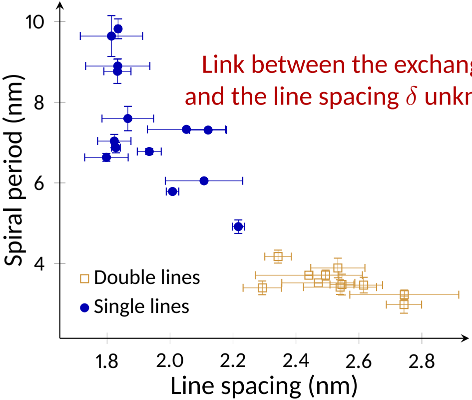
- Is strain changing the exchange coupling?
  Yes from *ab initio* calculations on a free standing Fe(110) layer.

T. Shimada *et al.* *Ab initio* study of spin-spiral noncollinear magnetism in a free-standing Fe(110) monolayer under in-plane strain. *Phys. Rev. B* 85.13 (2012).

Simple micromagnetic model

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

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



Link between the exchange A and the line spacing δ unknown!

$D = 2.8\,\mathrm{mJ\,m^{-2}}$

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

$\updownarrow$

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

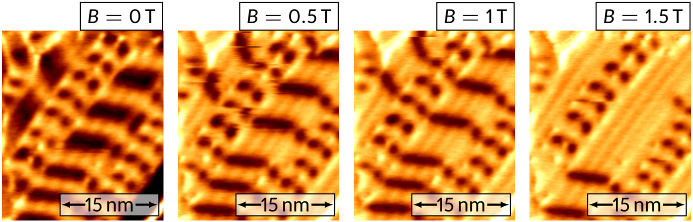
PdFe/Ir(111): $A = 2.0\,\mathrm{pJ\,m^{-1}}$

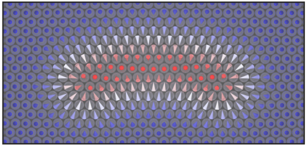
A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *J Magn. Magn. Mater.* 138.3 (1994).

N. Romming *et al.* Field-Dependent Size and Shape of Single Magnetic Skyrmions. *Phys. Rev. Lett.* 114.17 (2015).

Field dependence

Zoom in on the double line regions



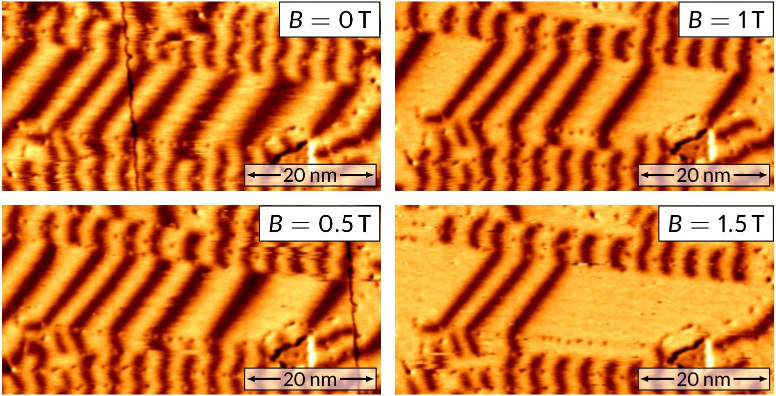


- Spirals split up into skyrmions
- These skyrmions are aligned on the reconstruction lines
- They can be isolated around 3 T
- FM state reached around 4 T

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

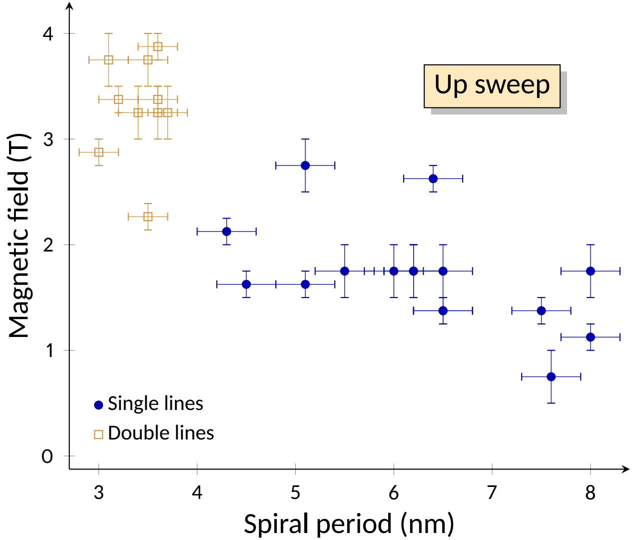
Field dependence

Zoom in on the single line regions



- Dark stripes (360° DW) get thinner, move and disappear
- FM state reached at 2 T
- No skyrmions here, different pinning?

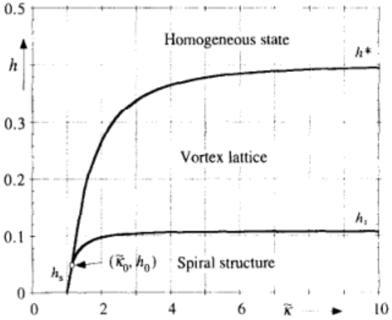
Dependence of the transition field on the spin spiral period



Back to the micromagnetic model

Model with a Zeeman term:

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



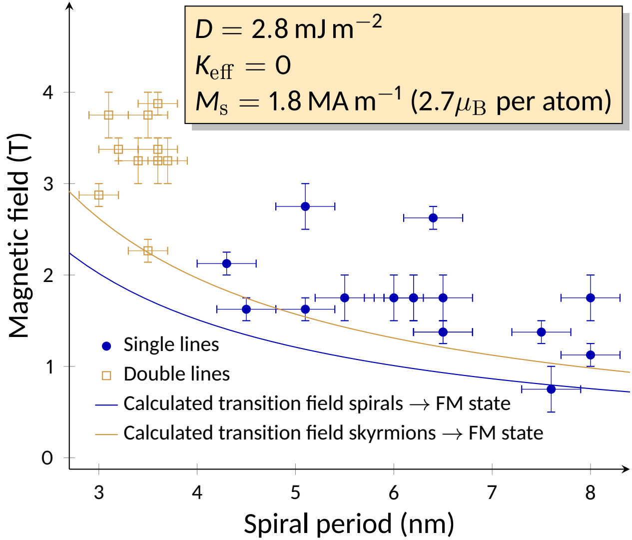
$$B_{\mathrm{t}} = \frac{D^2 h_{\mathrm{t}}}{A M_{\mathrm{s}}} = 4\pi \frac{D h_{\mathrm{t}}}{\lambda M_{\mathrm{s}}}$$

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

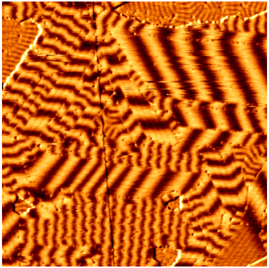
$$h_{\mathrm{t}}^{\mathrm{skyrmion}}(K_{\mathrm{eff}} = 0) = 0.401$$

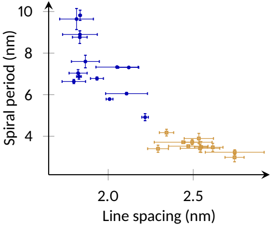
A. Bogdanov *et al.* Thermodynamically stable magnetic vortex states in magnetic crystals. *J Magn. Magn. Mater.* 138.3 (1994).

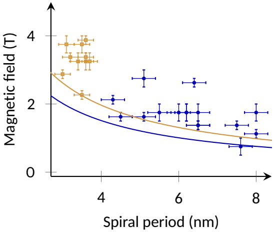
Dependence of the transition field on the spin spiral period



Summary







- Two types of dislocation lines, with different spirals at zero field, with skyrmions or DW in magnetic field.
- The spiral period depends on the line spacing, the strain relief affects the exchange coupling.
- The magnetic field needed to reach the FM state also depends on the line spacing, which is consistent with the micromagnetic model.

Acknowledgments

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Dr. Kirsten von Bergmann
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Universität Hamburg

MAGicSky

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