Modifying non-collinear magnetism with strain, temperature and electric field

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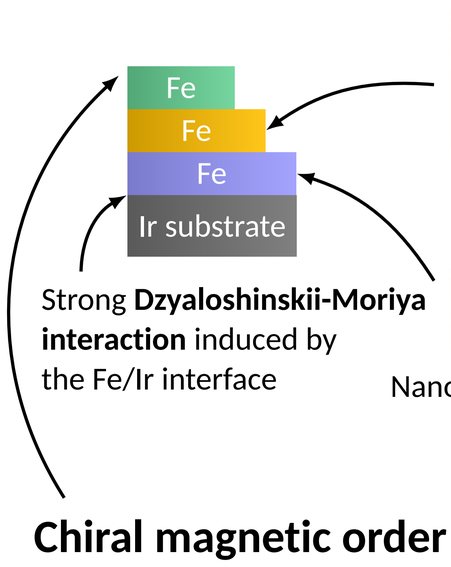
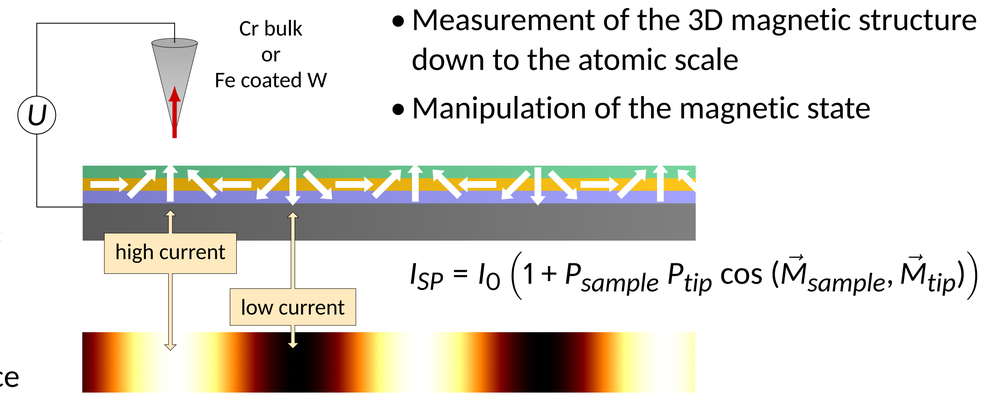
Fe on Ir(111)



Spin-polarized STM



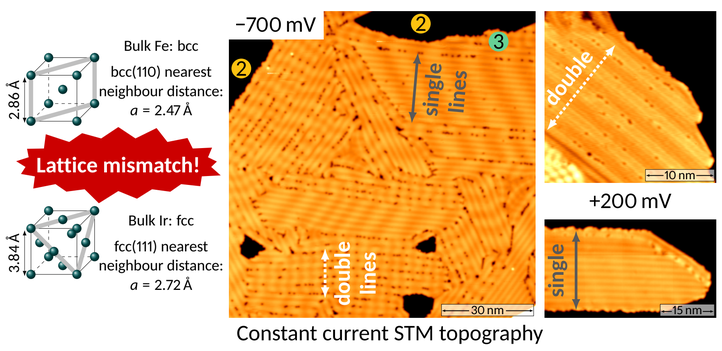
- Measurement of the 3D magnetic structure down to the atomic scale
- Manipulation of the magnetic state

Main findings

- Cycloidal spin spirals with a unique rotational sense propagate along the dislocation lines in the triple layer Fe on Ir(111).
- Variations of the strain relief in the triple layer Fe on Ir(111) can change the spin spiral periods via large modifications of the effective exchange coupling.
- The spin spiral periods increase significantly between 8 K and room temperature. This can be modeled by coupled magnetic layers with different interaction strengths.
- Skyrmions appear in magnetic field. They can reliably be written and deleted using electric field.

Chiral magnetic order at low temperature in the triple layer Fe on Ir(111)

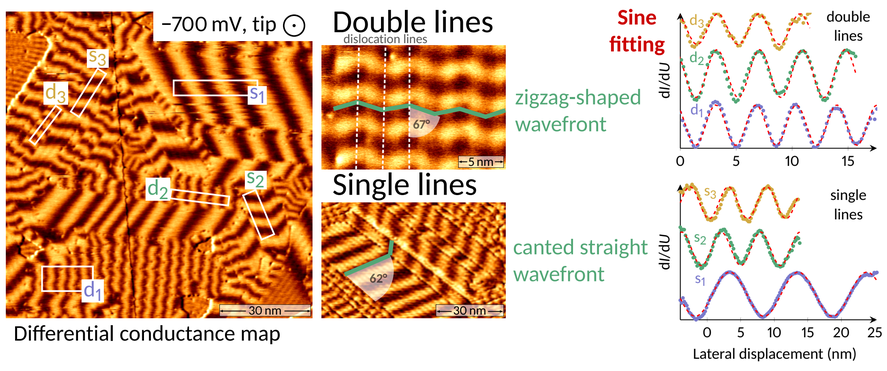
Reconstructed Fe film



Constant current STM topography

- A dense dislocation line network forms to **relieve the epitaxial strain**.
- The lines are oriented along the high-symmetry [1$\bar{1}$2] directions of the fcc(111) surface.
- Two types of lines can be distinguished: **double lines** and **single lines**.

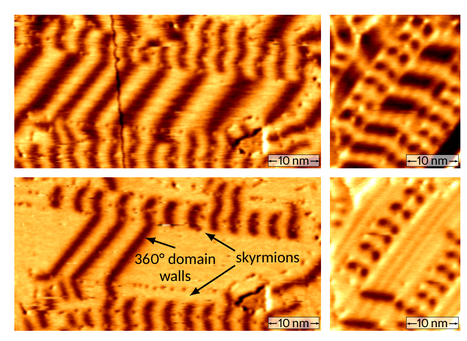
Homogeneous spin spirals along the dislocation lines



Differential conductance map

- **Cycloidal spin spirals** propagate along the dislocation lines.
- Their periods are between 3 and 4 nm in the double line areas and between 5 and 10 nm in the single line areas.
- They have a sinusoidal shape, indicating that the **magnetic anisotropy** is small. It is thus **neglected** in the following.

Skyrmions and domain walls in magnetic field

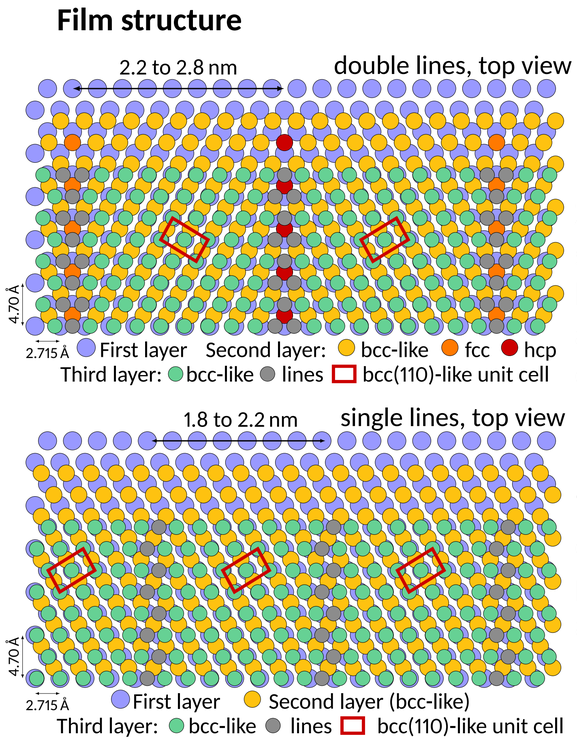


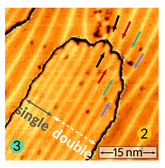
- **Skyrmions** are created in magnetic field in the double line areas.
- In the single line areas, only **360° domain walls** can be found.
- This could be explained by the **different pinning** properties of the two types of lines.

Influence of strain relief on the spin spiral periods

PRB, 94, 214402 (2016)

Film structure



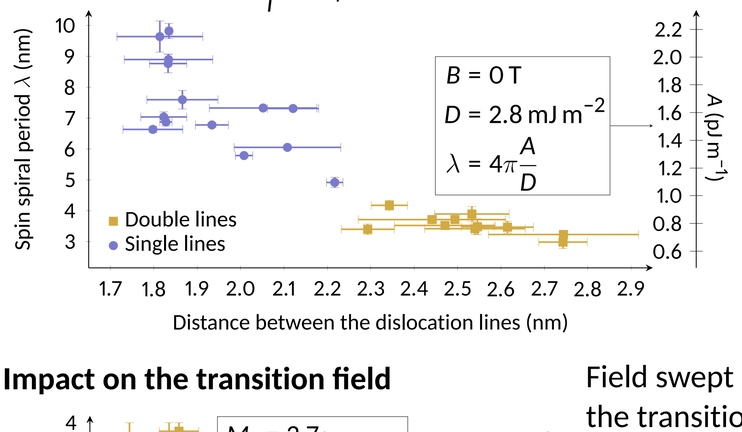


Zigzag-shaped spin spiral wavefront because of the **alternating** orientation of the **bcc-like unit cells**.

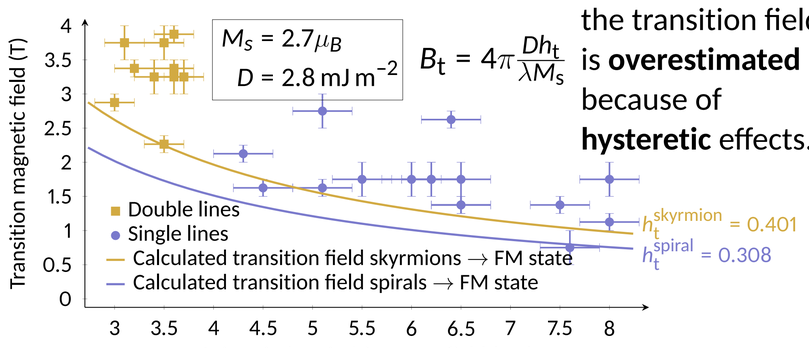
The **fixed** orientation of the **bcc-like unit cells** produces a **straight** and **canted** wavefront.

Effect of the strain relief on the effective exchange coupling

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



Impact on the transition field



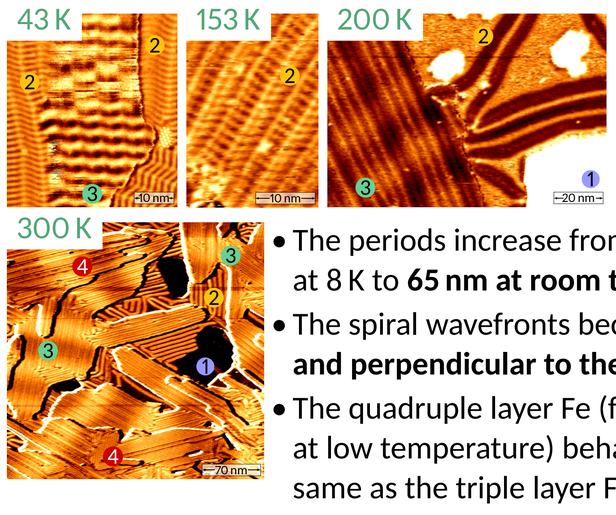
Field swept **up**, thus the transition field is **overestimated** because of **hysteretic** effects.

Temperature-induced increase of the spin spirals periods

arXiv:1703.10849

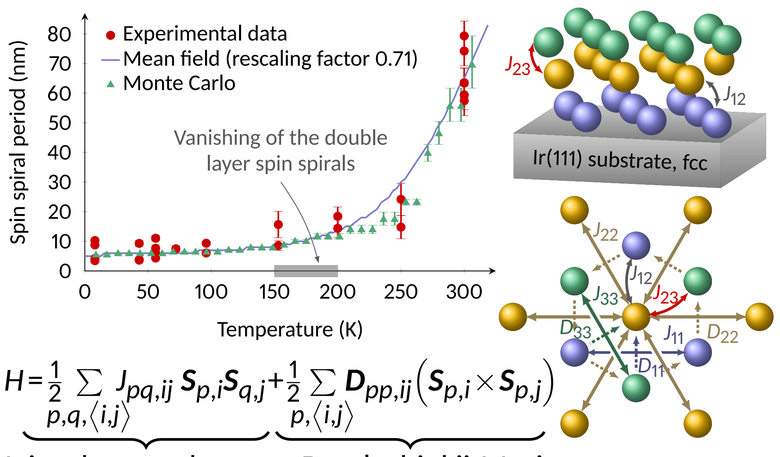
Improved thermal stability

Vanishing of the magnetic contrast
- Monolayer Fe: **28 K** PRL, 113, 077202 (2014)
- Double layer Fe: **between 150 and 200 K**
- Triple layer Fe: **above room temperature**



- The periods increase from 3 to 10 nm at 8 K to **65 nm at room temperature**.
- The spiral wavefronts become **straight and perpendicular to the lines**.
- The quadruple layer Fe (ferromagnetic at low temperature) behaves the same as the triple layer Fe.

Theoretical modeling of the period increase



$$H = \underbrace{\frac{1}{2}\sum_{p,q,\langle i,j\rangle} J_{pq,ij}\, \boldsymbol{S}_{p,i}\boldsymbol{S}_{q,j}}_{\text{Heisenberg exchange interactions}} + \underbrace{\frac{1}{2}\sum_{p,\langle i,j\rangle} \boldsymbol{D}_{pp,ij}\left(\boldsymbol{S}_{p,i} \times \boldsymbol{S}_{p,j}\right)}_{\text{Dzyaloshinkii-Moriya interactions}}$$

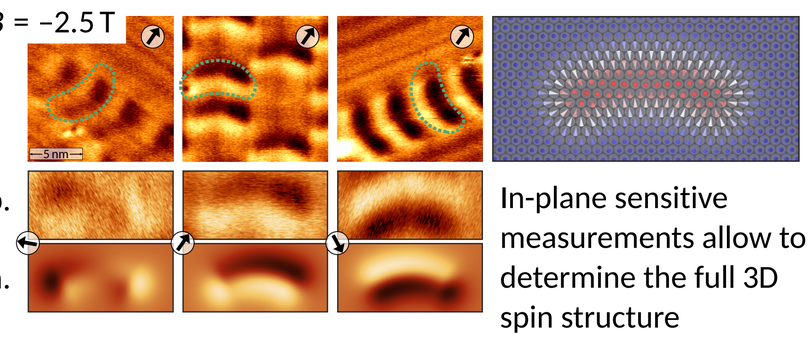
J_{11}	J_{22}	J_{33}	J_{12}	J_{23}	D_{11}	D_{22}	D_{33}
−8.75 K	−70 K	−245 K	−175 K	−65.63 K	87.5 K	43.75 K	0.88 K

- We use **different parameters in the three layers**.
- The mean field order parameter $\langle S_p(k)\rangle$ **decreases faster with temperature** in the first and second layers than in the third one. This **shifts the minimum of the free energy towards larger periods**.
- Good agreement between experiments, mean field calculations and Monte Carlo simulations.

Electric field switching of magnetic skyrmions

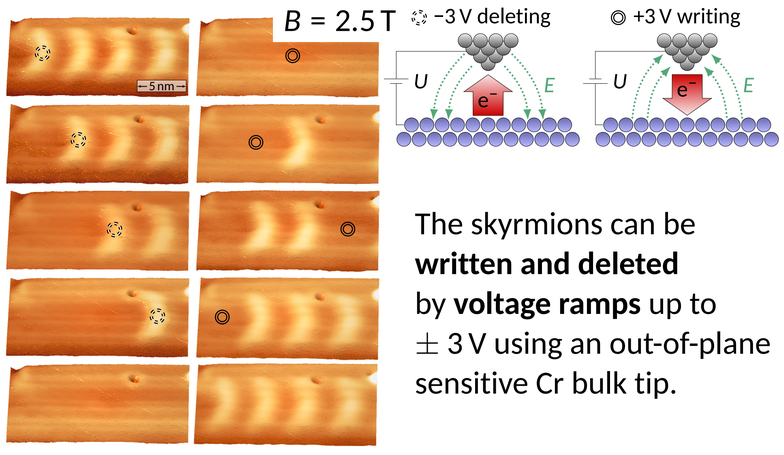
Nat. Nanotechnology, 12, 123-127 (2017)

Skyrmion structure



In-plane sensitive measurements allow to determine the full 3D spin structure

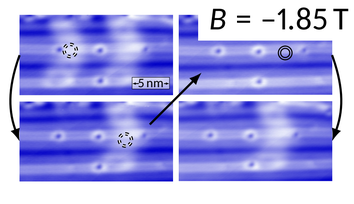
Reliable switching with an STM tip

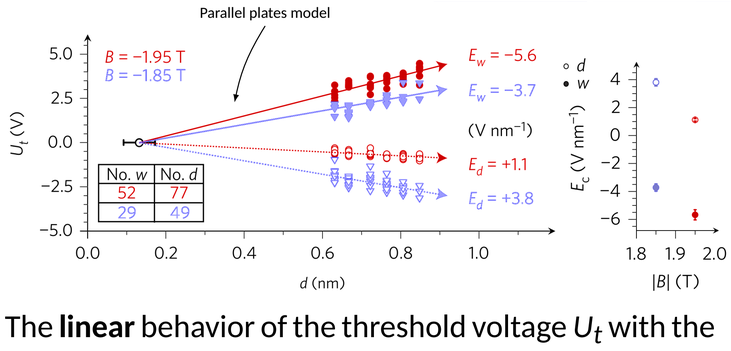


The skyrmions can be **written and deleted** by **voltage ramps** up to ± 3 V using an out-of-plane sensitive Cr bulk tip.

Role of electric field

The switching is also possible with a **non magnetic W tip**.





The **linear** behavior of the threshold voltage U_t with the tip-sample distance d demonstrates the **dominant role of the electric field in the switching mechanism**.