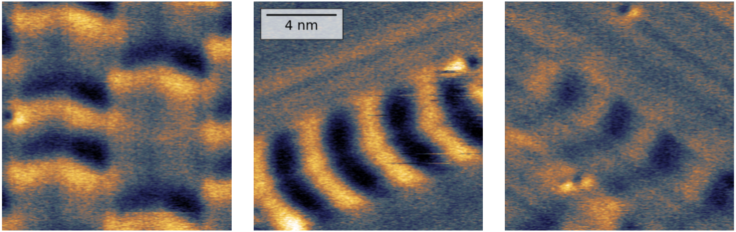
Universität Hamburg

MAGic Sky

# Temperature and field dependent SP-STM investigation of the non-collinear magnetic structures of several layers of Fe on Ir(111)

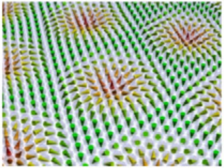
*Aurore Finco, Pin-Jui Hsu, Niklas Romming, Thomas Eelbo, Lorenz Schmidt, André Kubetzka, Kirsten von Bergmann and Roland Wiesendanger*

University of Hamburg, Germany

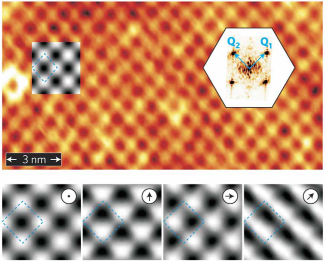


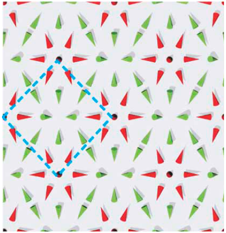
# Skyrmions in ultrathin films

- Skyrmions: topologically non trivial magnetic objects
- Interesting for spintronics applications (racetrack memories)
- Stabilized in ultrathin films by the interface-induced **Dzyaloshinskii-Moriya interaction** (ex: PdFe/Ir(111))



## Fe/Ir(111): nanoskyrmion lattice



Nanoskyrmion lattice visible until 28 K

**How to improve thermal stability ?**


A. Fert, V. Cros, and J. Sampaio. Skyrmions on the track. *Nature nanotechnology* 8.3 (2013).

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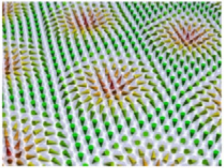

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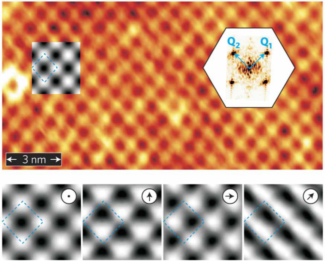


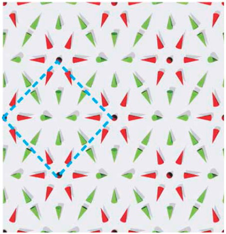

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**How to improve thermal stability ?**

↓

**Go to higher coverage**

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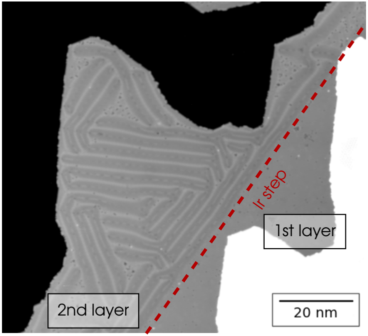
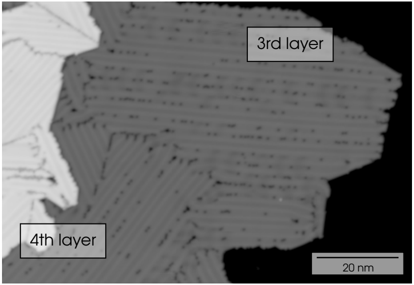
# Morphology of the Fe films on Ir(111)

- lattice mismatch between Fe and Ir
- Fe deposition at elevated temperature (around 200 °C)
- 1st layer **pseudomorphic** (strained)
- **reconstruction lines** along the 3 equivalent crystallographic directions on the thicker layers (uniaxial strain release)




Topography, $U = 200\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 4\,\mathrm{K}$, $B = 0\,\mathrm{T}$, W tip

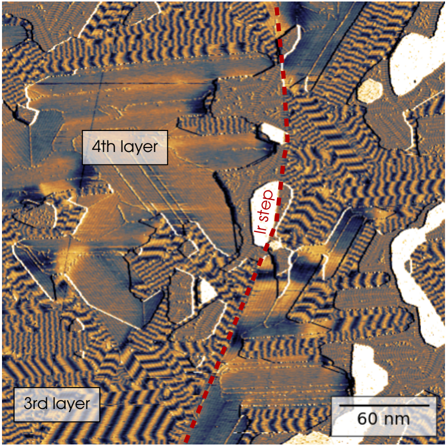



Topography, $U = -700\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 4\,\mathrm{K}$, $B = 2.5\,\mathrm{T}$, Cr bulk tip

**Strong influence of the surface structure on the magnetic order**

# Non-collinear magnetic structure

*Low temperature, without external magnetic field*




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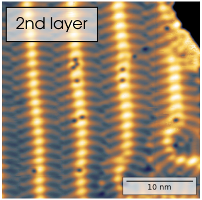


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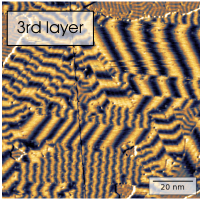


Differential conductance,
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- **Cycloidal spin spirals guided by the lines on the 2nd and 3rd layers**
- **Ferromagnetic domains on the 4th layer**

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

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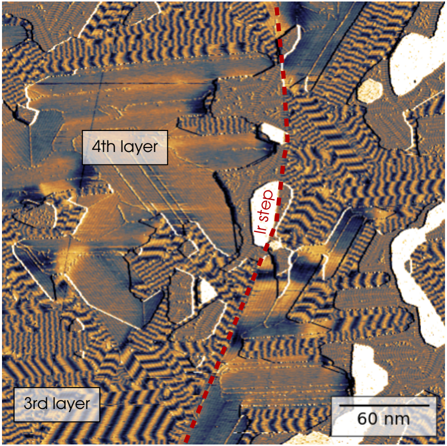


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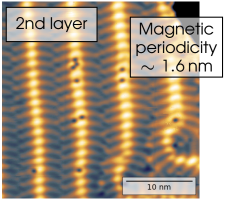


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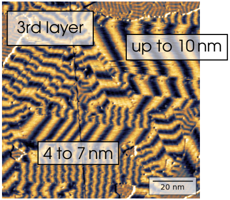


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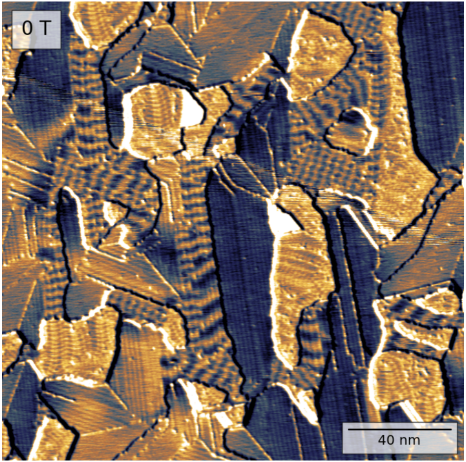
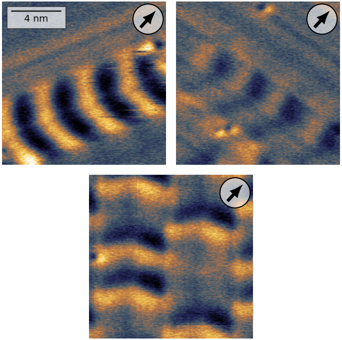
# Application of an external out-of-plane magnetic field

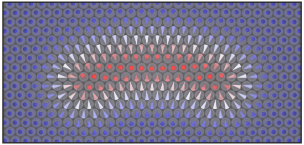
- No effect on the 2nd layer up to 9 T.
- On the 3rd layer, single magnetic objects appear around 1.5 T.




Differential conductance, $U = -500\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 4\,\mathrm{K}$, Cr bulk tip with out-of-plane magnetic sensitivity




Differential conductance, $U = -700\,\mathrm{mV}$, $I = 1\,\mathrm{nA}$, $T = 8\,\mathrm{K}$, $B = -2.5\,\mathrm{T}$, Cr bulk tip



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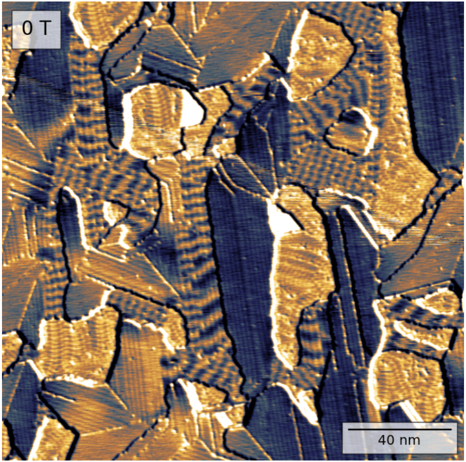


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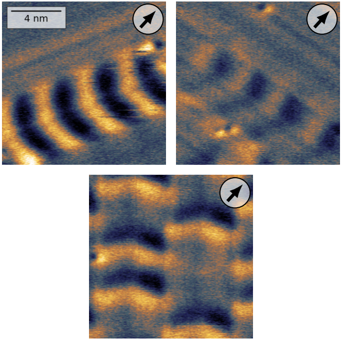


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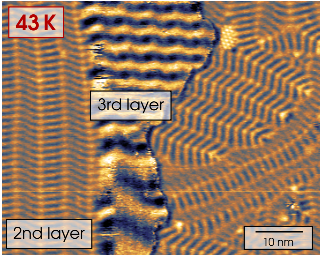
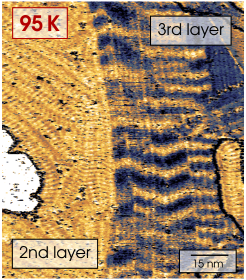
# Temperature dependence

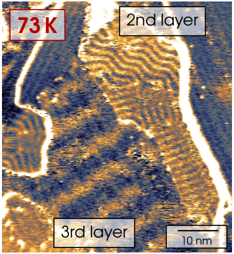
- Spin-polarized measurements with a Fe coated W tip
- Temperature increased in several steps, **no external magnetic field**



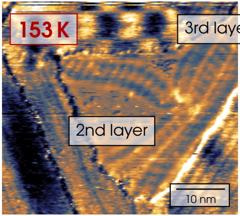

Differential conductance, $U = -0.7\,\mathrm{V}$, $I = 0.7\,\mathrm{nA}$




Differential conductance, $U = 0.7\,\mathrm{V}$, $I = 1\,\mathrm{nA}$

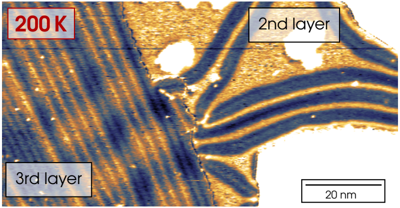


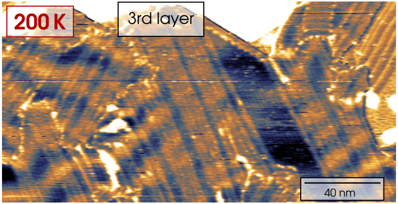

Differential conductance, $U = -1.3\,\mathrm{V}$, $I = 1.5\,\mathrm{nA}$



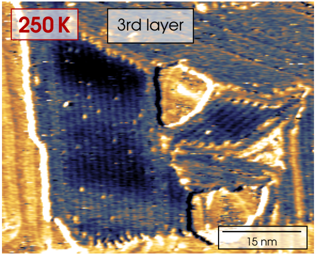

Differential conductance, $U = -0.5\,\mathrm{V}$, $I = 2\,\mathrm{nA}$

# Temperature dependence

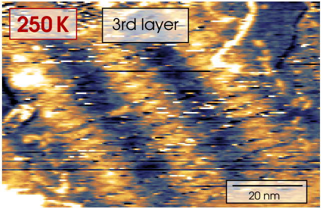



Differential conductance, $U = -0.7\,\mathrm{V}$, $I = 2\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip

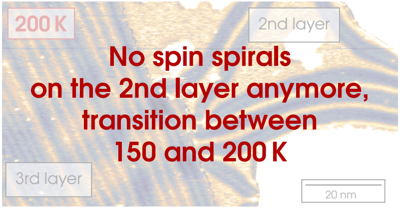


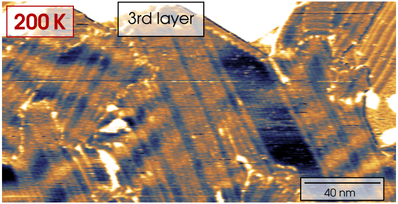

Differential conductance, $U = -0.5\,\mathrm{V}$, $I = 5\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip



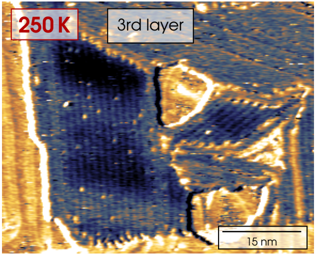

Differential conductance, $U = -0.7\,\mathrm{V}$, $I = 3\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip

# Temperature dependence

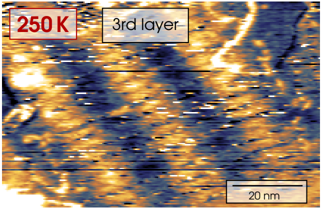



Differential conductance, $U = -0.7\,\mathrm{V}$, $I = 2\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip




Differential conductance, $U = -0.5\,\mathrm{V}$, $I = 5\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip




Differential conductance, $U = -0.7\,\mathrm{V}$, $I = 3\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip

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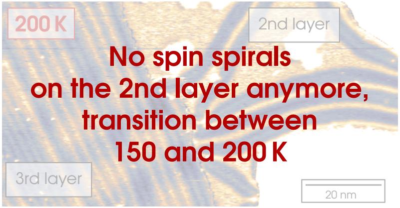
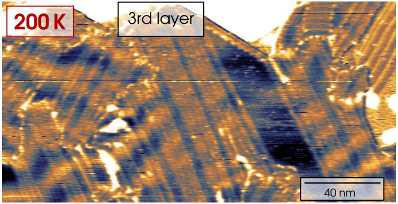



**No spin spirals on the 2nd layer anymore, transition between 150 and 200 K**

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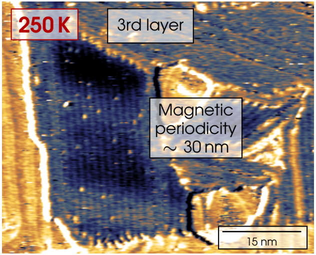
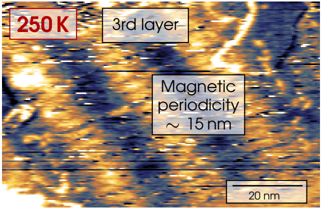


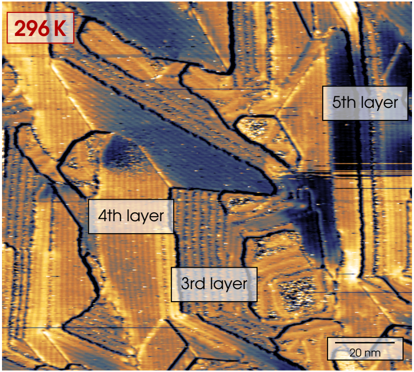

Differential conductance, $U = -0.5\,\mathrm{V}$, $I = 5\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip




Differential conductance, $U = -0.7\,\mathrm{V}$, $I = 3\,\mathrm{nA}$, $B = 0\,\mathrm{T}$, Fe coated W tip

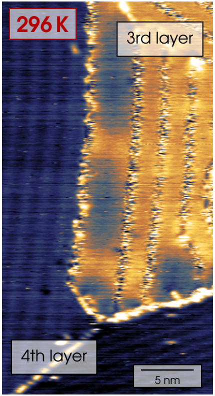
**3rd layer:**
- **Periodicity increase**
- **Different shape of the wave front**

# Room temperature magnetic structure




Differential conductance, $U = -0.7\,\text{V}$, $I = 1\,\text{nA}$, $B = 0\,\text{T}$, Fe coated W tip

- Ferromagnetic domains (and switching) still visible on the 4th and 5th layers
- No spirals visible on the majority of the 3rd layer areas



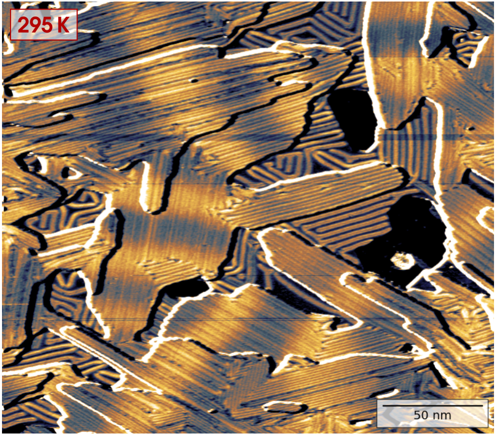

Differential conductance, $U = -0.7\,\text{V}$, $I = 1\,\text{nA}$, $B = 0\,\text{T}$, Fe coated W tip

- Only a few small 3rd layer spots exhibit a magnetic pattern

**Effect of the stray field of the ferromagnetic tip?**

# Non-collinear magnetism at room temperature

## Switch to an antiferromagnetic Cr bulk tip




Differential conductance, $U = -0.5\,\mathrm{V}$, $I = 3\,\mathrm{nA}$, $B = 0\,\mathrm{T}$

# Non-collinear magnetism at room temperature

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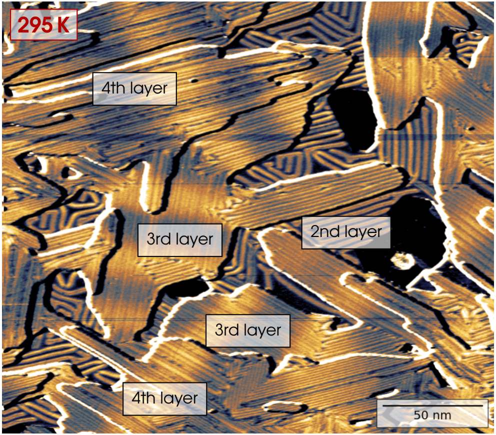
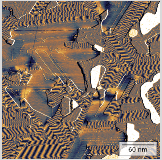


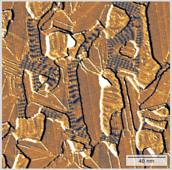

Differential conductance, $U = -0.5\,\mathrm{V}$, $I = 3\,\mathrm{nA}$, $B = 0\,\mathrm{T}$

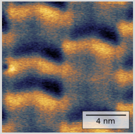
- Spin spirals visible on the 3rd, 4th and 5th layers.
- Direction of the wavevector still given by the reconstruction lines
- Straight wavefront perpendicular to the lines
- The spirals are crossing the different layers
- Periodicity between 60 and 80 nm

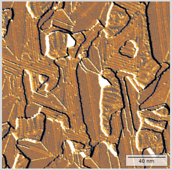
# Summary

## External magnetic field (low temperature)




2nd & 3rd layers: spin spirals
4th layer: FM domains

4th layer: FM

3rd layer:
distorted skyrmions

3rd layer: FM

$B = 0\,\mathrm{T}$ $B = 1\,\mathrm{T}$ $B = 2.5\,\mathrm{T}$ $B = 4\,\mathrm{T}$

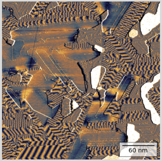
## Temperature (no field)

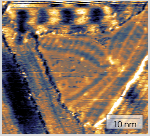
$T = 4\,\mathrm{K}$ $T = 150\,\mathrm{K}$ $T = 200\,\mathrm{K}$ $T = 300\,\mathrm{K}$

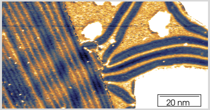
3rd layer:
Periodicity $\leq 10\,\mathrm{nm}$
Canted wavefront

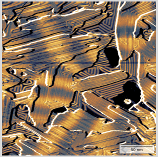
2nd layer transition

3rd layer:
Periodicity $60 - 80\,\mathrm{nm}$
Straight wavefront



# Acknowledgments


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

Universität Hamburg

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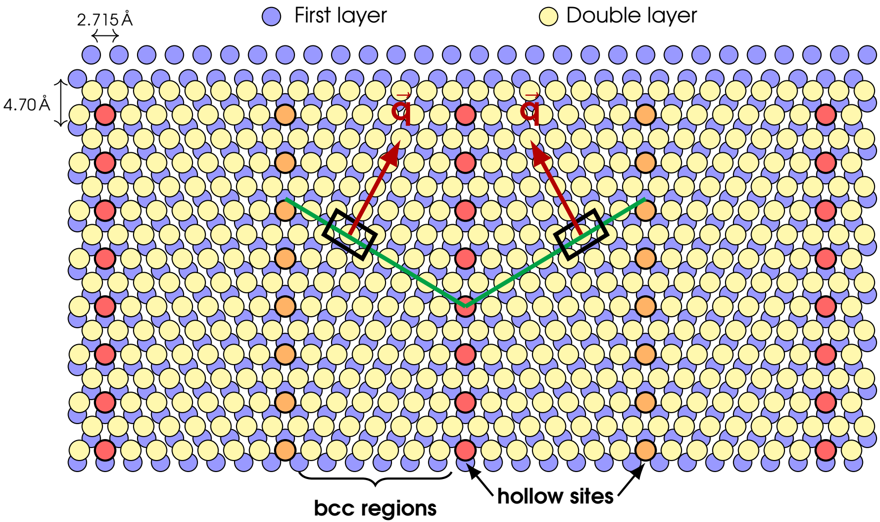
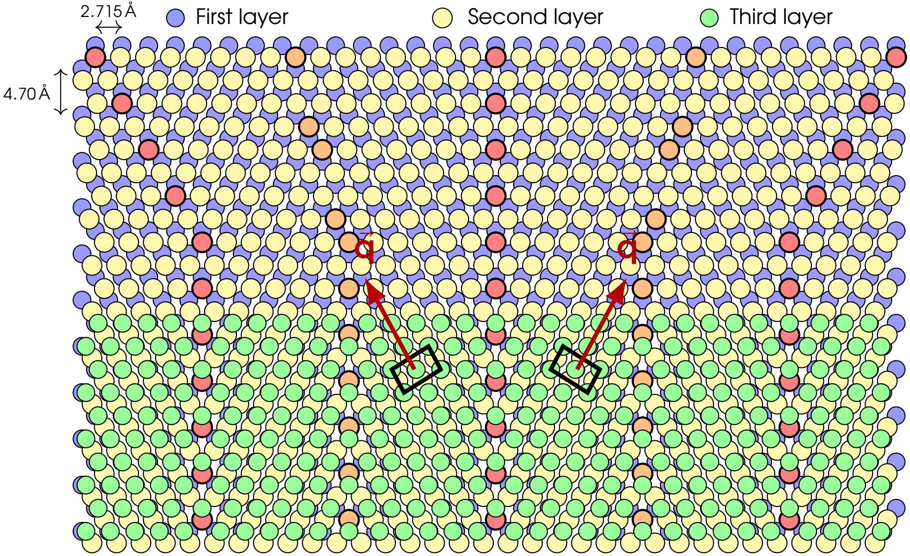
Funded by the Horizon2020 Framework Programme of the European Union

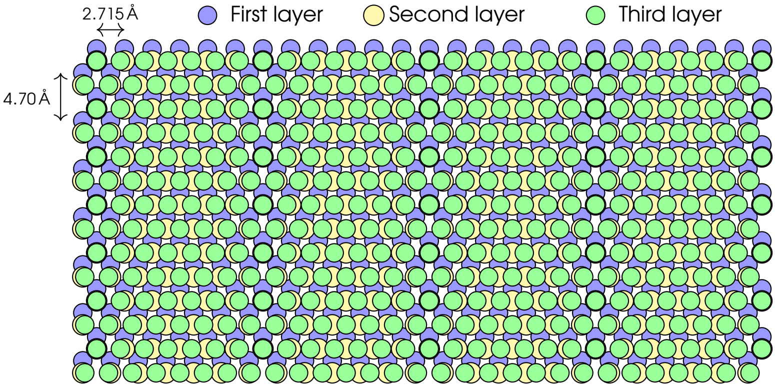
# Structural model for the double layer



# Structural model for the double lines areas



# Structural model for the dense lines areas




- Epitaxial double layer below (non-reconstructed areas)
- Distorted bcc(110) Fe layer on top

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Bai An et al. Growth and structural transition of Fe ultrathin films on Ni(111) investigated by LEED and STM. . *Phys. Rev. B* 79 (8, 2009), page 085406.