Nanoscale Mechanics of Antiferromagnetic Domain Walls

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LETTERS

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Nanoscale mechanics of antiferromagnetic domain walls

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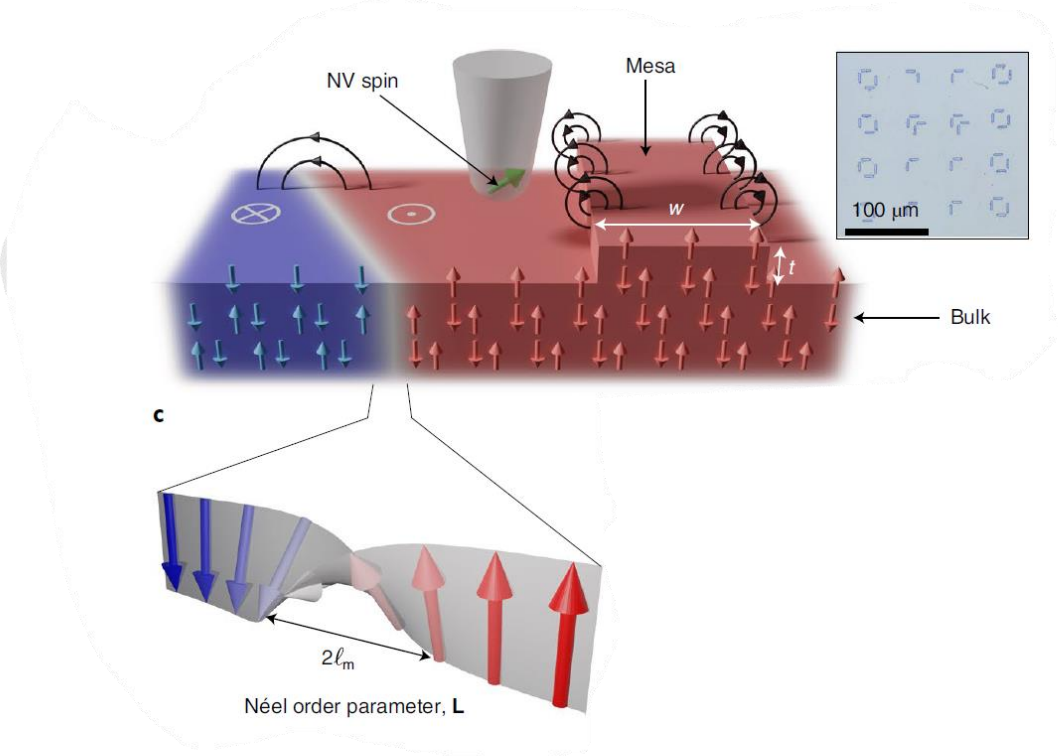
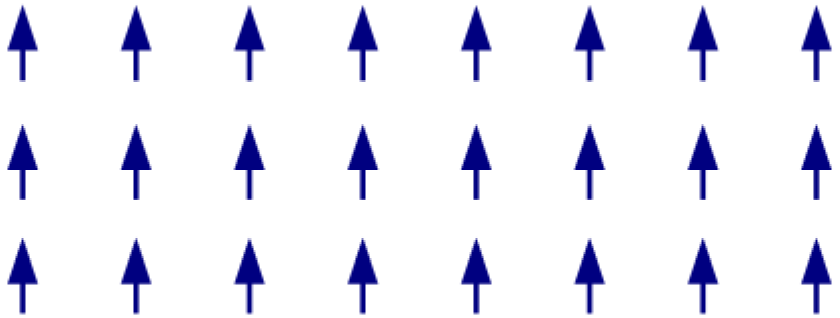
Outline

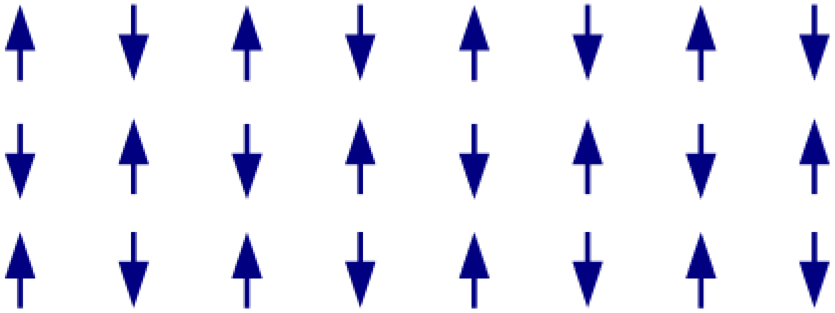
- Motivation
- Nitrogen-vacancy magnetometry
- AFM Domain Wall
- Applications



Antiferromagnetism



Ferromagnetism



Antiferromagnetism

Antiferromagnetic materials are more abundant than ferromagnets in nature, however, they have been studied less due to their vanishing magnetization and insensitivity to applied fields.

Antiferromagnetic materials

In recent years, antiferromagnetic materials has been extensively studied

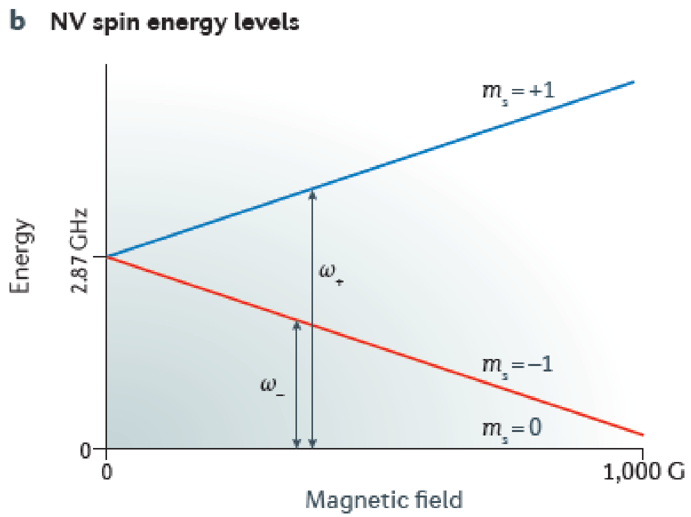
- Understanding fundamental magnetic properties
- Technique Development
  - Visualization
  - Control
- Antiferromagnetic spintronics
- Potential applications

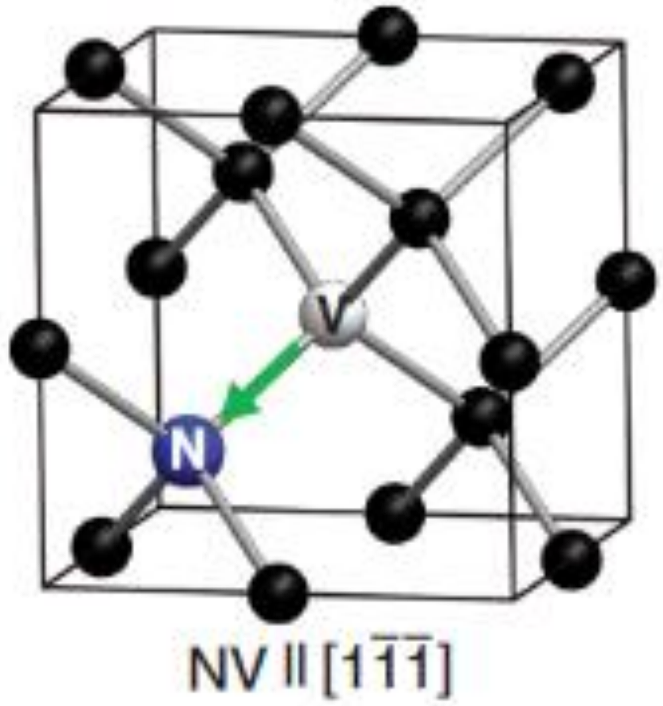
Visualizing AFM Domains

- Difficulty : zero net magnetic moment

- Techniques:
  - Nitrogen-vacancy Center
  - Spin-polarized scanning tunneling microscopy
  - Magnetic force microscopy
  - synchrotron X-rays
  - ...

Nitrogen-vacancy Center

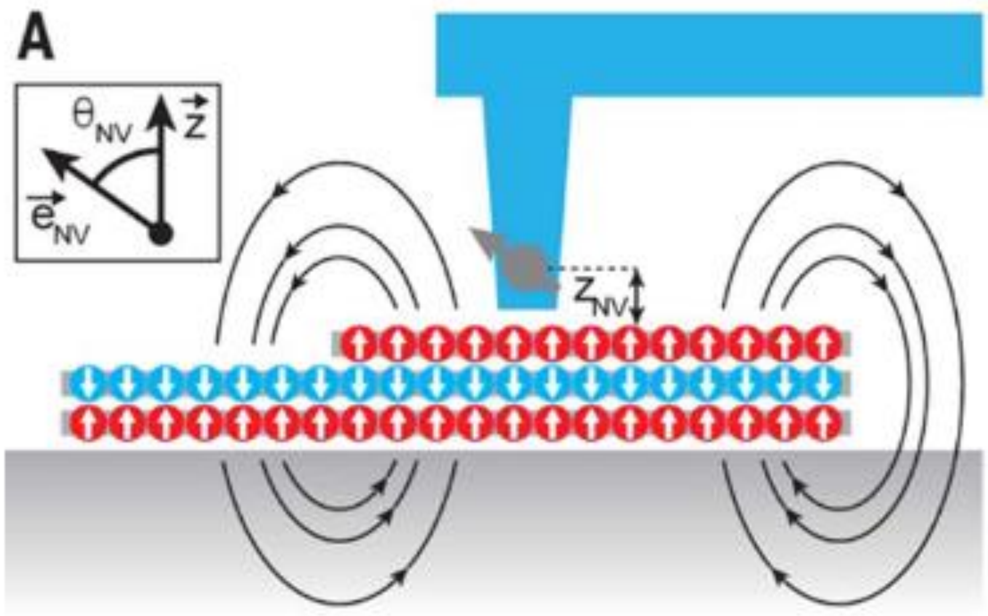




- The use of NV centers as magnetic-field sensors was first proposed in 2008
- Negatively charged state: 2 unpaired electron
- NV center exhibits a Zeeman splitting caused by the local magnetic field
- Zeeman shift can be read out optically
- Excellent magnetic and spatial resolution

Rev. Mod. Phys. **92**, 015004 (2020).
Nat. Rev. Mater. **3**, 17088 (2018).

Scanning NV magnetometry



- Attaching a diamond nanocrystal to the atomic force microscopy tip
- Stray field
- Nanometer-scale spatial resolution

- Robust against varying operating temperature and pressures

Science 364, 973 (2019).

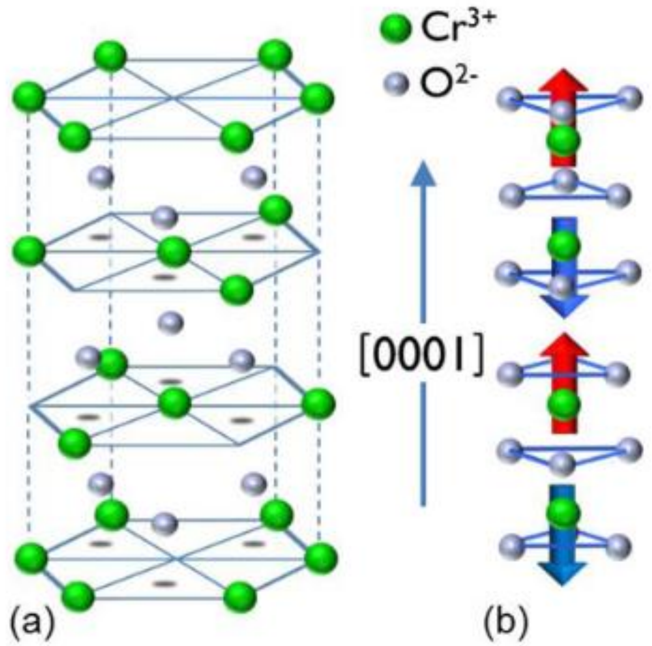
Cr_2O_3

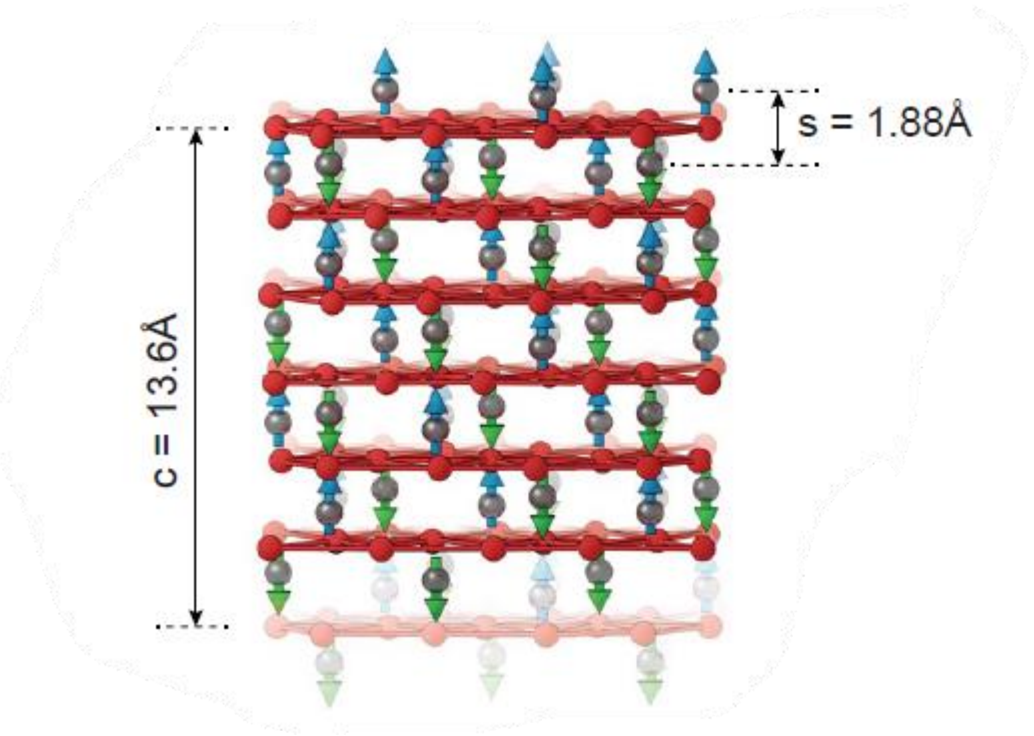
- Antiferromagnetic insulators
- Uniaxial
- Neel temperature ~ 307 K (Around room temperature)
- Magnetoelectric effect

$$P_i = \sum_j \epsilon_0 \chi^e_{ij} E_j + \sum_j \alpha_{ij} H_j$$

$$\mu_0 M_i = \sum_j \mu_0 \chi^v_{ij} H_j + \sum_j \alpha_{ij} E_j$$

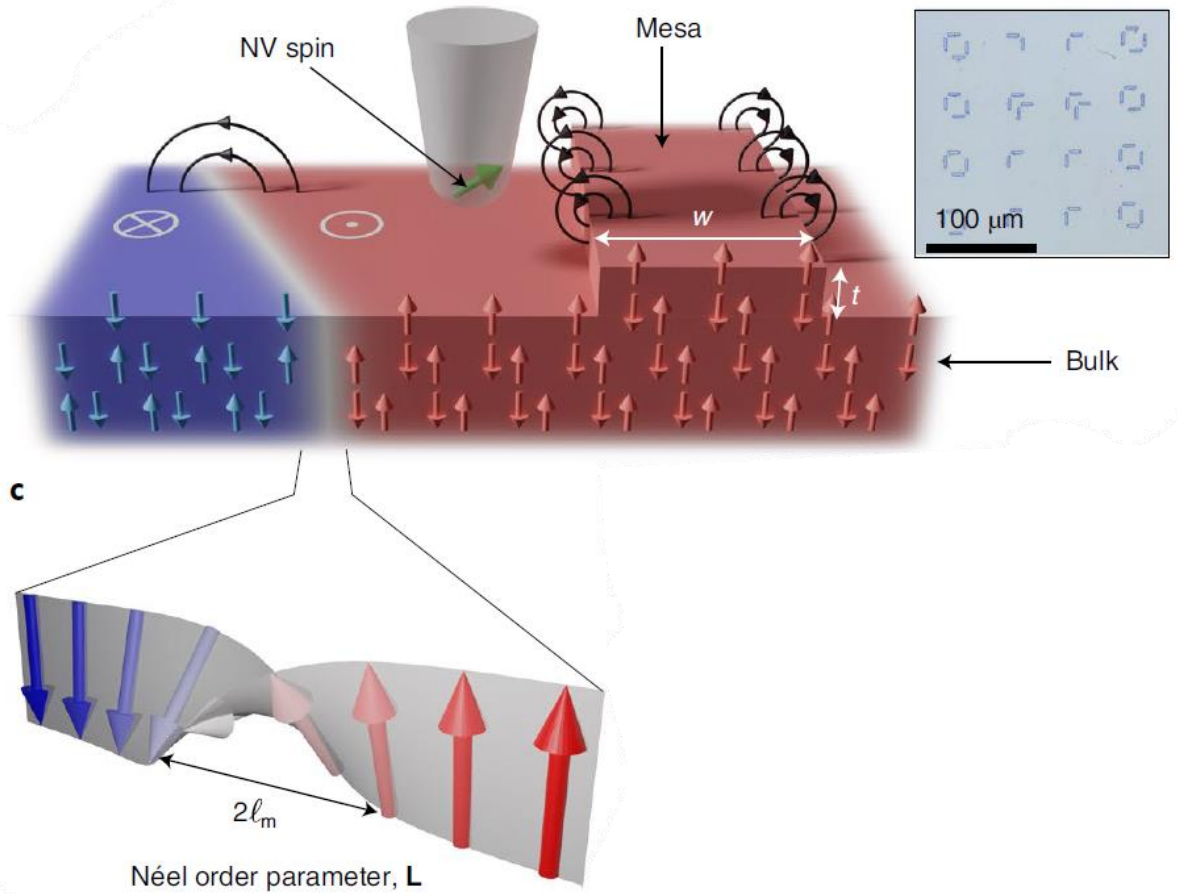
Structure





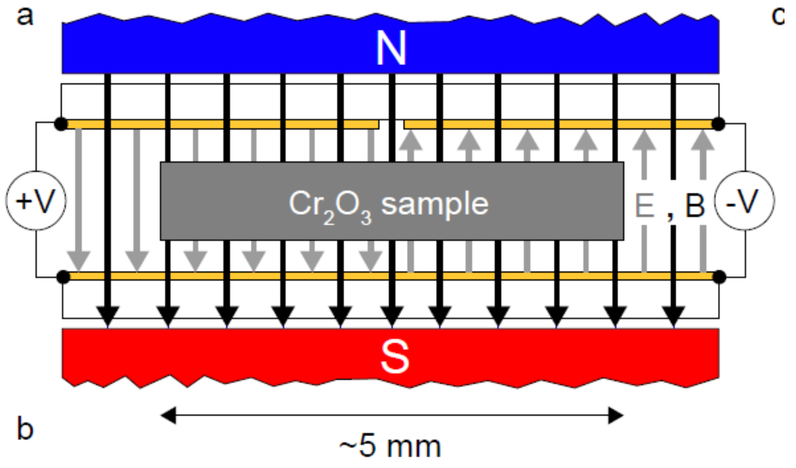
Hexagonal structure

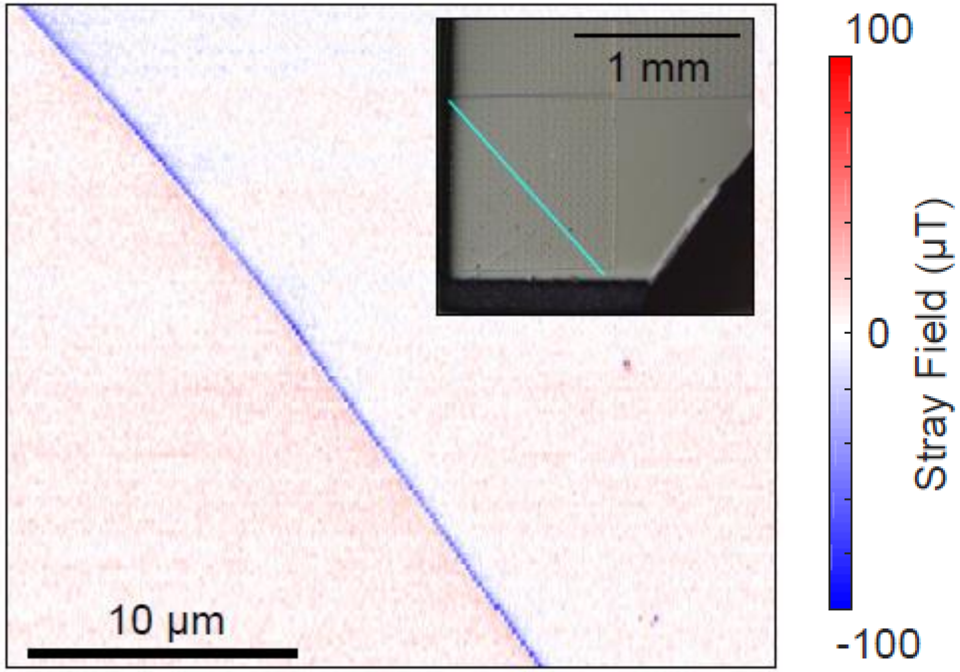
Phys. Rev. B **91**, 214403 (2015)
Phys. Rev. B **103**, 094426 (2021)



- (0001)-oriented Cr_2O_3 single crystal
- Thickness of 1 mm and millimetre-scale lateral dimensions
- Electron-beam lithography
- Mesas: t= 166±4nm, w= 2.4 ±0.3um

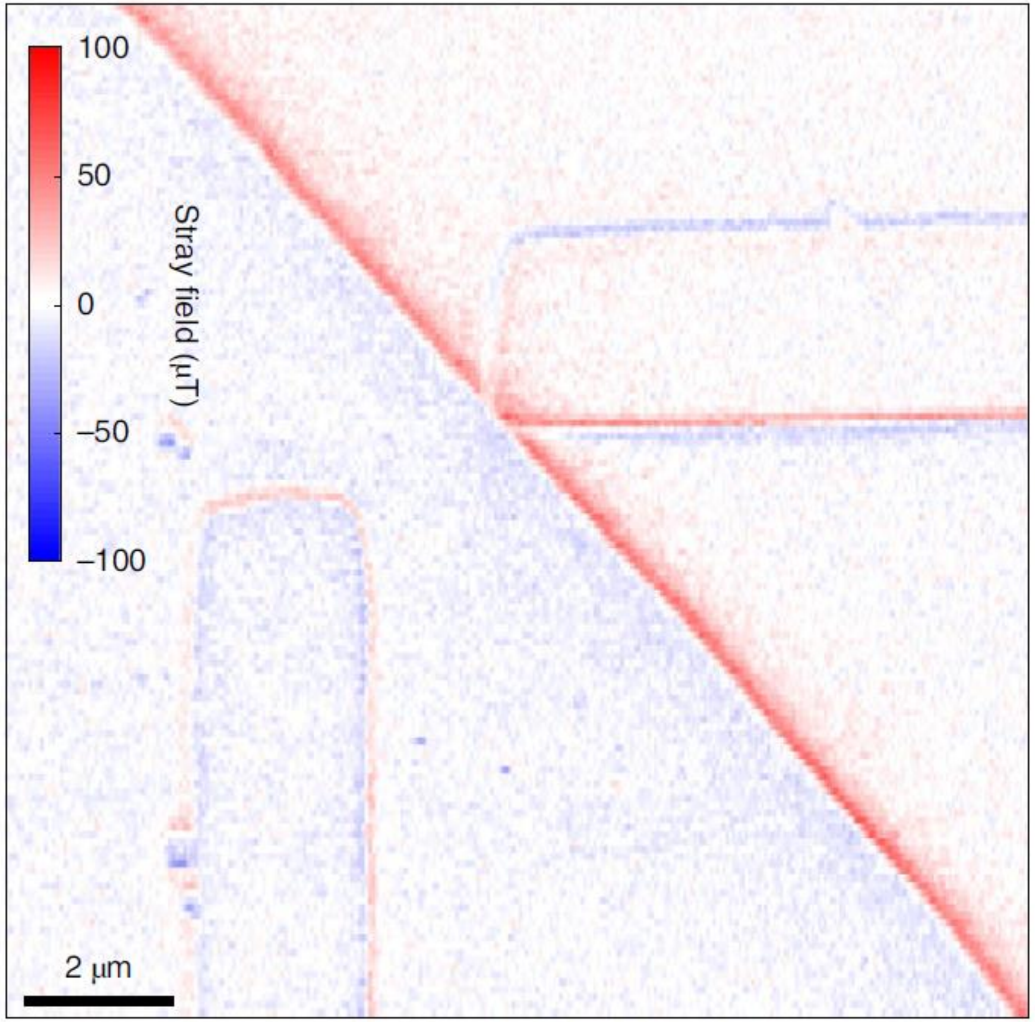
Domain Wall Nucleation

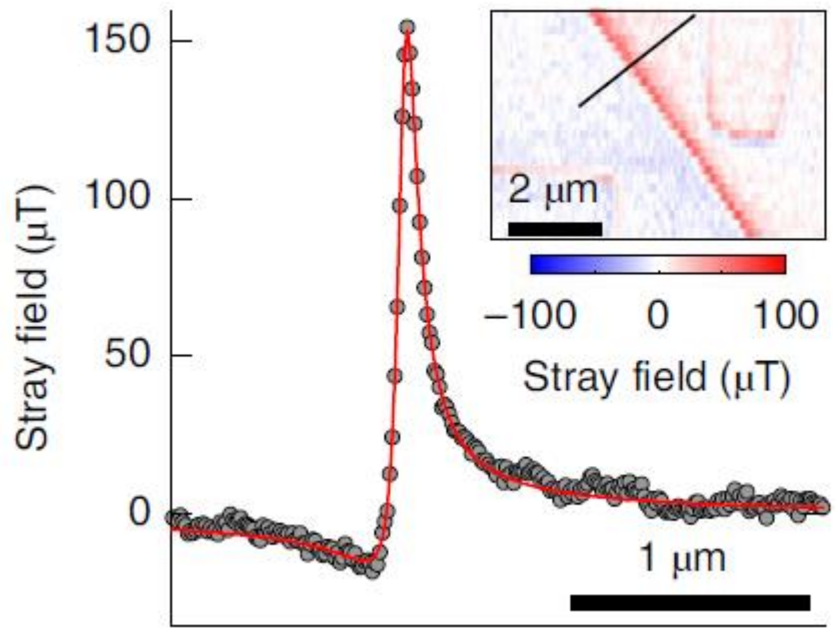




- Induce magnetic domains by magnetoelectric field cooling across T_N
- B_{bias} = 550 mT and E_{bias} = ±0.75 MV m^{-1}

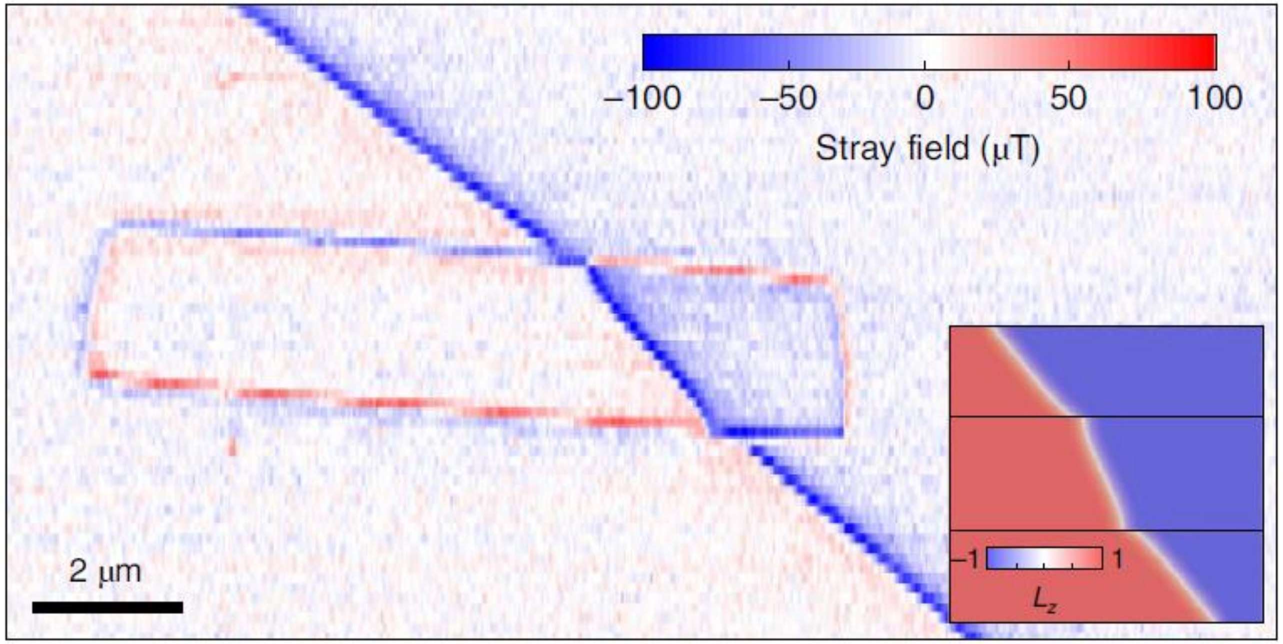
AFM domain wall (DW)





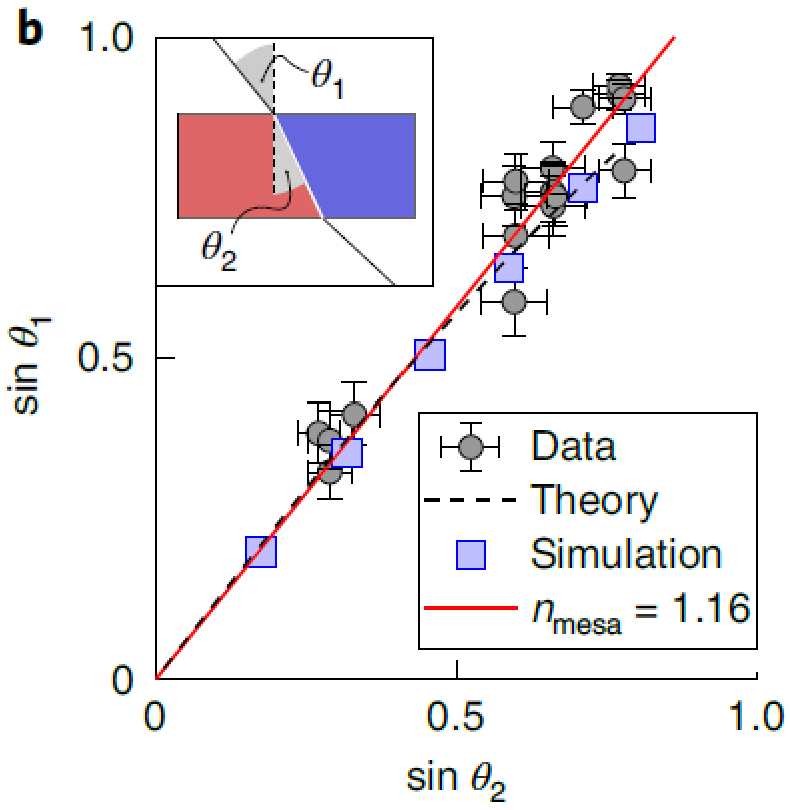
- $\ell m \lesssim 32$ nm from the fitting data (red curve)

DW crosses a mesa



- Deviations from the straight DW paths
- Refraction-like behavior
- Numerical simulation is in good agreement

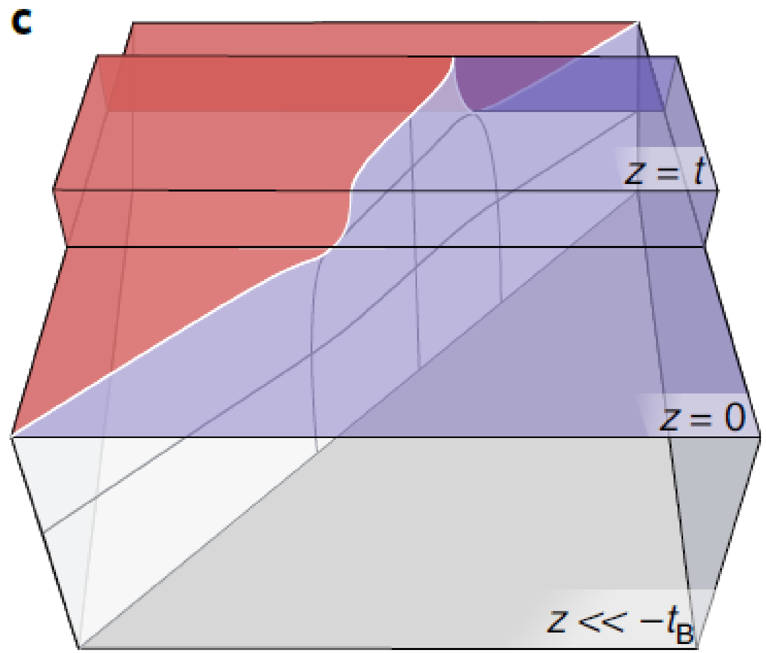
Snell’ law



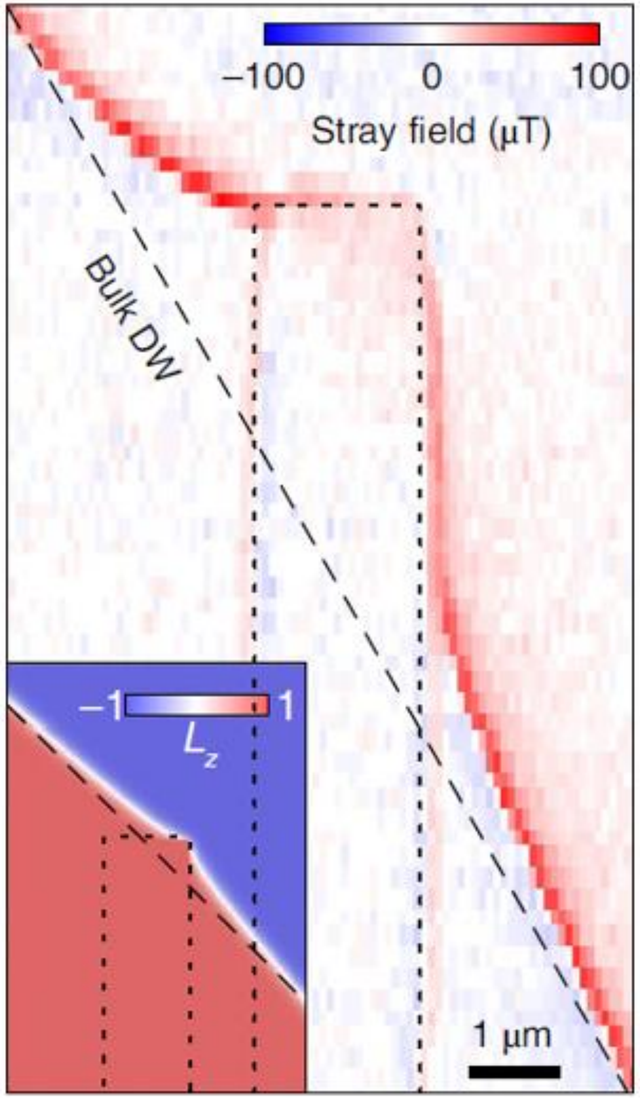
- $\vartheta 1 \in \{\sim 20° \ldots \sim 70°\}$
- $\sin \vartheta 1 / \sin \vartheta 2 = 1.16 \pm 0.04$
- Spin lattice simulations
- Analytical results
  - Refractive index $n_{mesa} = \sin \vartheta 1 = \sin \vartheta 2$
  - Small angles $\vartheta 1 \ll 1$, $n_{mesa} = 1 + 3.1(t/w) +$ higher-order term
- Difference
  - Snell’s law: principle of least action alone
  - DW trajectory: with higher-order contributions

Spin lattice simulations

- Considering
  - Nearest-neighbour AFM exchange interactions
  - Single-site anisotropy
  - Sample geometry
- S-shape distortion: minimization of the exchange interaction by normal incidence of DWs to surfaces
- Three-dimensional morphology: DW twists in the bulk

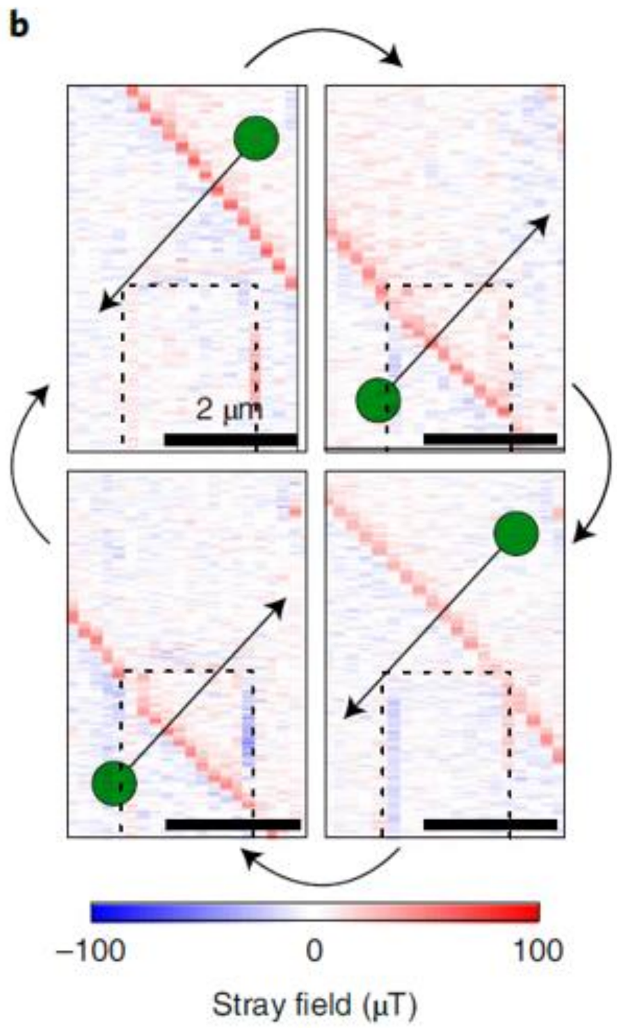


DW-Pinning at mesa edges



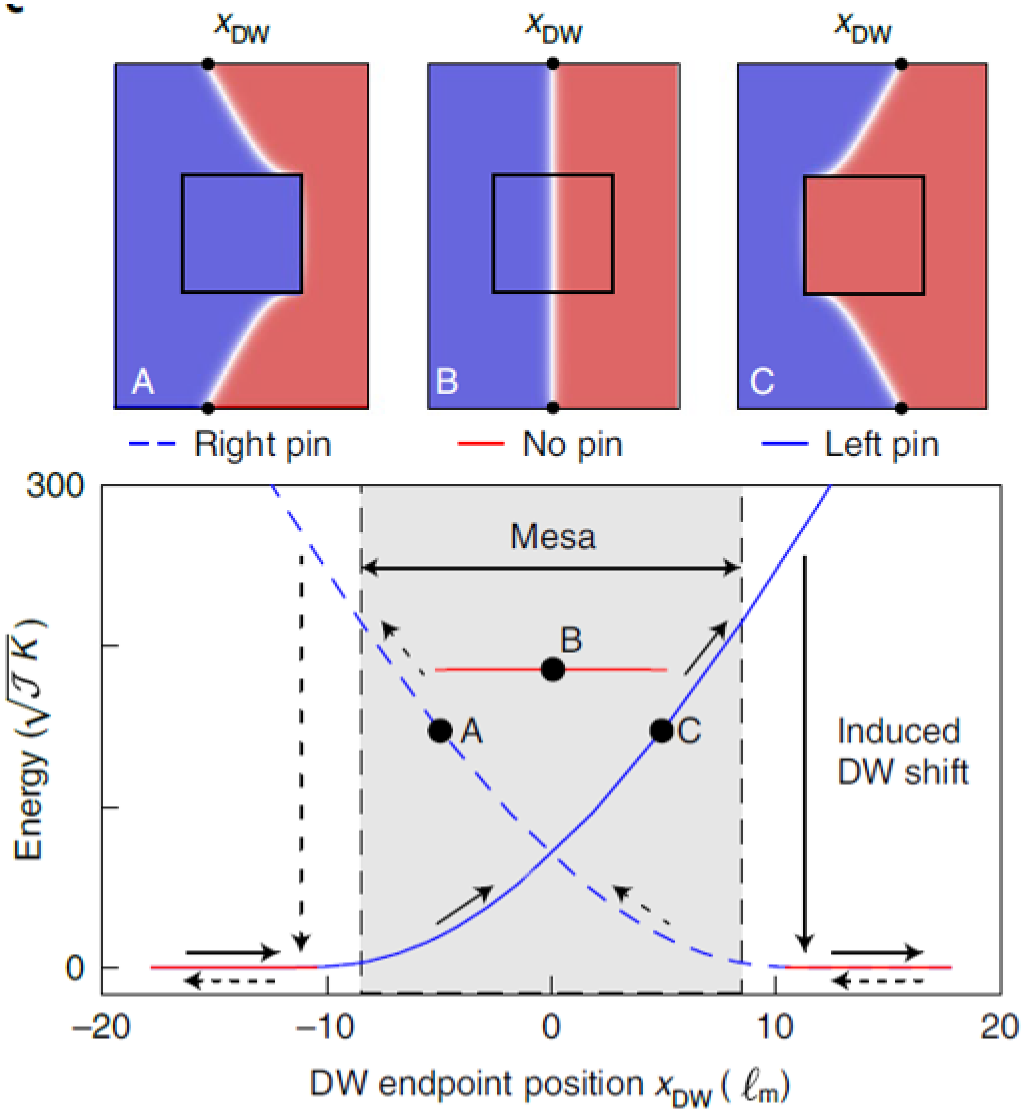
- Energy penalty
- Mesa: a large DW energy barrier
- Minimizes the overall energy
- DW path depends on:
  - Mesa geometry
  - Location with respect to the mesa
- Simulation is in good agreement

Domain Wall Dragging



- Focused laser spot
- Laser-induced heating reduces the DW energy locally
- Higher temperature makes DW dragging easier
- Reproducible
- DW manipulation

Pinning and switching behavior



- 3 distinct equilibrium DW states
- Crossing the mesa will cause energy increase (depend on the mesa height)
- Elastic and deformable (like rubber band)
- Metastable state
- Switching process can be controlled by mesa height and the strength of the stimulus

Applications

Ferromagnet-based device

REVIEW

Magnetic Domain-Wall Logic

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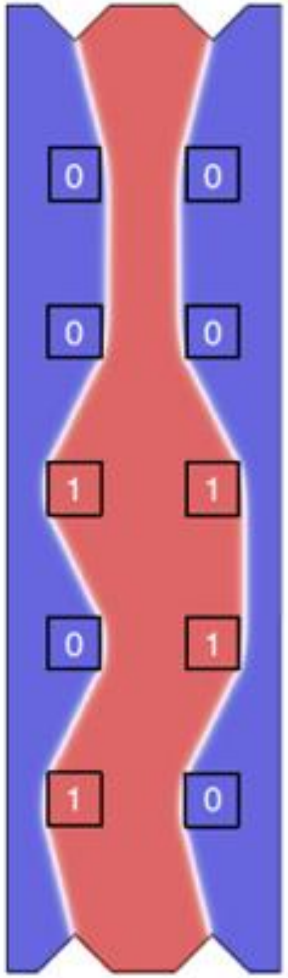
"Spintronics," in which both the spin and charge of electrons are used for logic and memory operations, promises an alternate route to traditional semiconductor electronics. A complete logic architecture can be constructed, which uses planar magnetic wires that are less than a micrometer in width. Logical NOT, logical AND, signal fan-out, and signal cross-over elements each have a simple geometric design, and they can be integrated together into one circuit. An additional element for data input allows information to be written to domain-wall logic circuits.

elements. Information propagates by magnetic solitons running across the lattice of interacting magnetic elements, and logic functions are performed by summing stray magnetic fields at nodal dots that have well-defined switching thresholds. One of the challenges with such schemes is that the magnetostatic interaction field between ferromagnetic elements is usual-

AFM-based memory devices



- Reading
- Switching
- Control

- Antiferromagnetic spintronics
  - Insensitive to disturbing magnetic fields
  - Would not magnetically affect its neighbors

Summary

- AFM DW behavior can be determined only by sample geometry and the DW surface energy

- Capability of visualizing and controlling the AFM DW
  - Understanding fundamental Physics
  - Leads to future research and applications

Questions?

- Do they have the results with different mesa dimensions? Consistent with the simulations and theory?
- After dragging the DW by the laser spot, how did they align the probe to the same location?
- Cr2O3 Thin film results (Same group): Domain contrast?

NANO LETTERS

ACS AUTHORCHOICE

Letter

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Nanomagnetism of Magnetoelectric Granular Thin-Film Antiferromagnets

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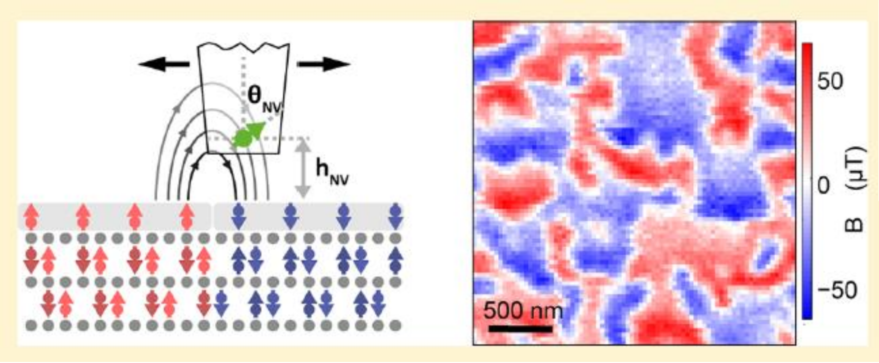

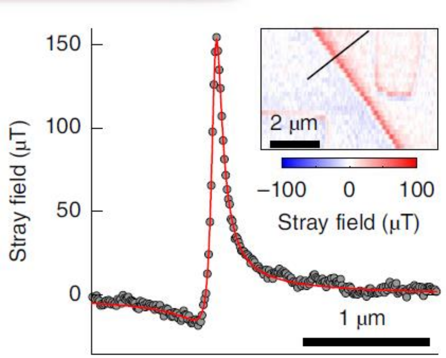

Thank you!